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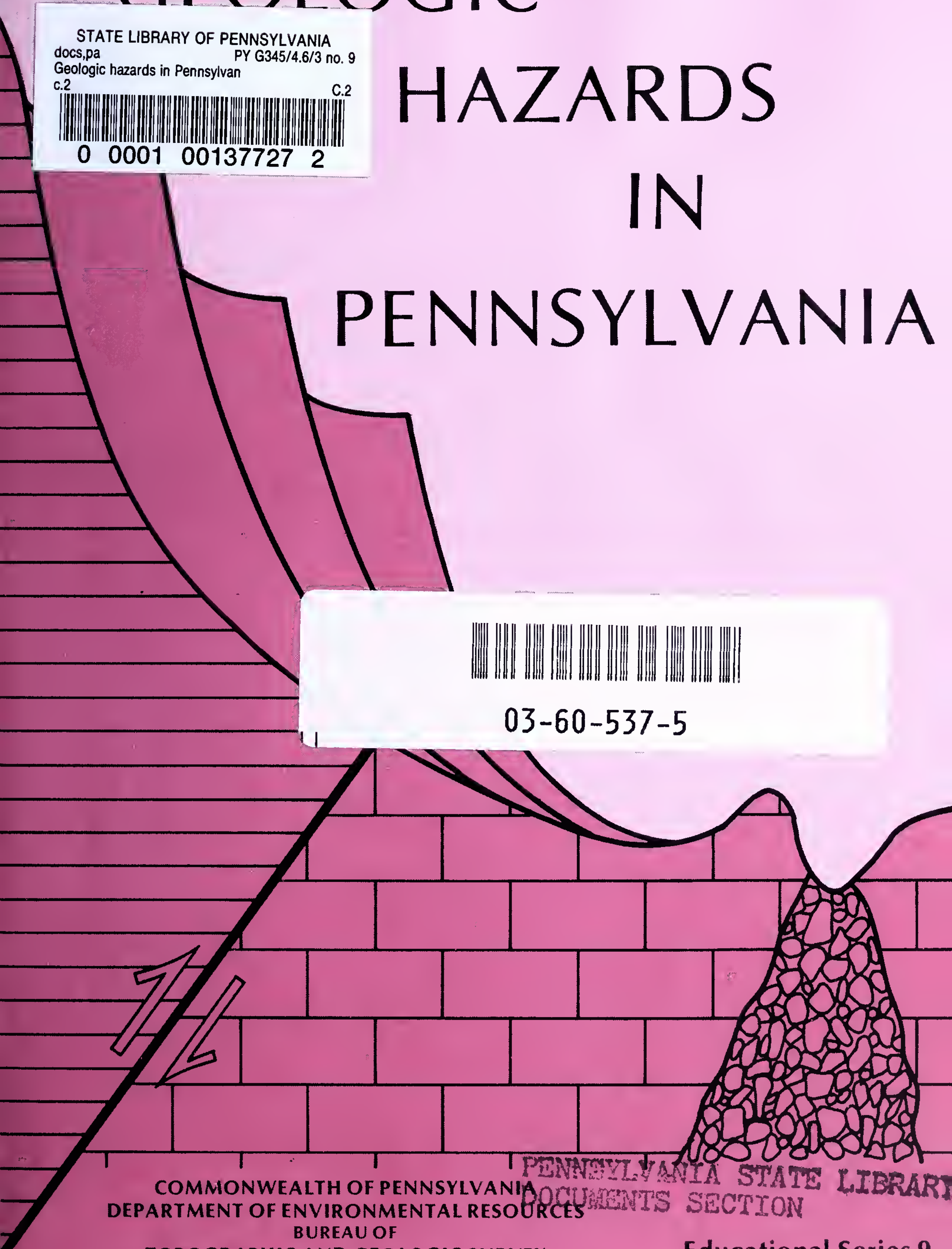

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Educational Series 9

GEOLOGIC HAZARDS IN PENNSYLVANIA

by J. Peter Wilshusen
Pennsylvania Geological Survey

Illustrations by Albert E. VanOlden

PENNSYLVANIA GEOLOGICAL SURVEY
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PREFACE

Geologic hazards of various kinds are common to almost every area of the world. Natural geologic hazards that most commonly receive attention in different parts of the world are earthquakes, volcanic eruptions, landslides, and sinkholes. In Pennsylvania the most frequent and widespread natural geologic hazards are landslides and sinkholes and other solution features. Earthquakes have not been of sufficient intensity in Pennsylvania to cause much concern but they are briefly discussed here. Descriptions of these hazards and an awareness of their distribution will help planners, local government officials, developers, and private citizens to recognize and deal with them in a timely and effective manner.

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GEOLOGIC HAZARDS IN PENNSYLVANIA

INTRODUCTION

There is a need in Pennsylvania to make information about geologic hazards available to the people of the commonwealth. Information about natural hazards is pertinent to planning and design for future development, to the protection of valuable private property that may be affected by a hazardous condition, and to the enlightenment of all who are interested in learning more about geologic conditions and earth processes.

Geologic hazards are natural physical conditions in the earth that present risks and may result in damage to the land, damage to structures, injury, or loss of life. Geologic hazards in Pennsylvania include landslides, sinkholes and other solution features, and, to a very minor degree, earthquakes. In some instances, man-induced conditions intensify geologic hazard occurrence, initiating landslides or stimulating sinkhole development.

This publication describes the more common geologic hazards of Pennsylvania and shows where they are likely to occur in the state (Figure 1). The effects of the activities of man on these occur-

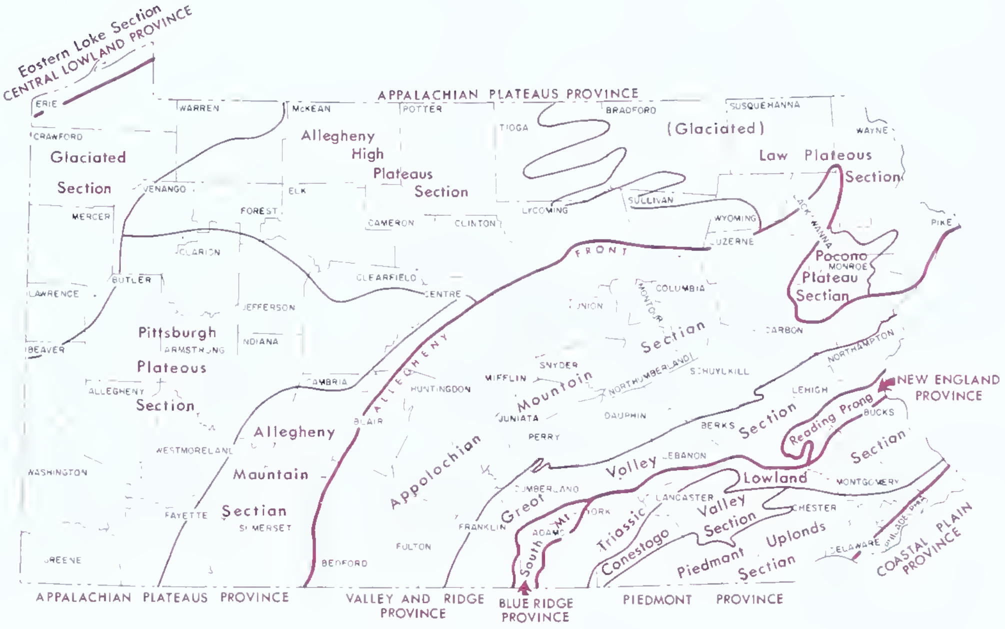


Figure 1. Physiographic provinces in Pennsylvania. The text refers to the physiographic names to designate areas of geologic hazard occurrence.

rences are examined and ways of minimizing the hazard potential are suggested.

Land subsidence due to underground mining and slope failures in man-made earth or rock embankments are not classed here as geologic hazards because they are not due to natural conditions; prior to construction or mining activity the ground was stable. In addition, flooding, although a natural hazard, is not considered here because it is not caused by instability of soil or bedrock.

The purpose, then, of this report is to make the reader aware of natural geologic conditions in Pennsylvania that may be hazardous.

LANDSLIDES

Geologic processes operating over millions of years have produced the irregular landscape of hills, valleys, mountains, cliffs, streams, and rivers that exists today. Because of the continuous action of geologic erosional processes upon the slopes of the landscape, rock and soil become unstable. As time goes on, portions of land move down hillsides under the influence of gravity.

The word "landslide" is a general term for this downslope mass movement of soil and rock and can generally be referred to as slope failure. Movement may be slow or fast, ranging from soil creep to rockfall, and the slope on which failure occurs may be gently inclined in some occurrences and steep to vertical in others. The moving mass may be saturated with water, damp, or dry. The material moves either by flowing, as in the case of soil creep and mudflow, or by sliding, as in the case of a rockslide down a surface of slippage. The surface on which movement occurs may be curved or it may be relatively straight. Using these variables, landslides can be classified and are named as shown in Table 1 (adapted from Sharpe, 1938).

Landslides are classified as either *flowage* or *sliding*. If movement takes place in which each portion of the moving mass moves independently, the movement is classified as *flowage*; flowage is then further classified on the basis of rate of movement into *slow flowage* and *rapid flowage*.

Rapid flowage is differentiated from slow flowage by the fact that the rate of movement is observable. It is usually due to the presence of sufficient water in the material to lubricate the mov-

Table 1. *Types of Landslides in Pennsylvania*

- SLOW FLOWAGE
  - Rock creep
  - Talus creep
  - Soil creep

- RAPID FLOWAGE
  - Earthflow
  - Mudflow
  - Debris avalanche

- SLIDING
  - Slump
  - Debris slide and debris fall
  - Rockslide
  - Rockfall

ing mass into rapid motion. Movement exhibits the behavior of a viscous fluid.

If there is a distinct surface of slippage along which the mass moves as a whole unit, the resulting occurrence is classified as *sliding*. An examination of the various types of slope failure within these landslide categories will demonstrate the distinction.

ROCK CREEP

Description

Rock creep is the slow downslope movement, due to gravity, of surficial rock fragments created by weathering (Figures 2 and 3). It is usually imperceptibly slow and can be measured only by observations of long duration. The presence of water or ice between the rock fragments lubricates the mass of material, permitting it to move downhill by flowage.

Although freezing and thawing and water are major causes of rock creep, there are others, including 1) expansion, contraction, and growth of plant roots resulting from periodic increase and decrease of water content; 2) expansion and contraction of soil and rock with changing temperature, resulting in a greater expansion downhill; and 3) the formation of desiccation (drying) cracks and their closing or filling, which causes a downslope component of movement.

Occurrence

Rock creep is widespread, occurring on almost every slope. Rock creep may take place on gentle slopes as well as steep ones

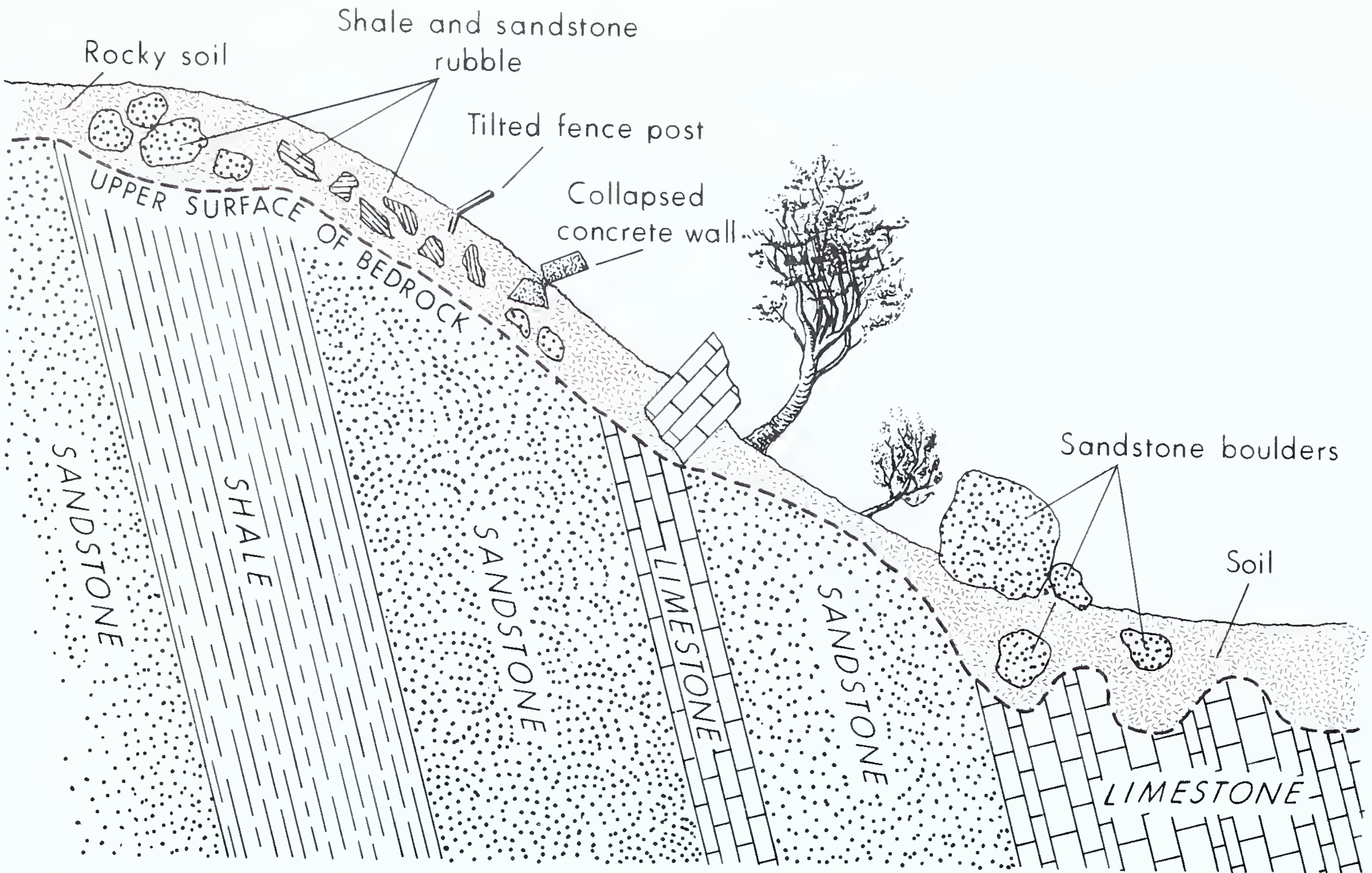


Figure 2. Characteristics of rock and soil creep shown in a cross section of a hillside. Sandstone boulders near the top of the hill have weathered away from the parent rock along fractures and have moved downhill. Similarly, shale fragments are in the soil downhill from their source rock. In the middle of the hillside a limestone block has tilted downhill. Near the toe of the slope, several sandstone boulders from above are buried or partially buried in soil over limestone. These situations are typical of conditions found along the crests of narrow ridges in the Valley and Ridge province.

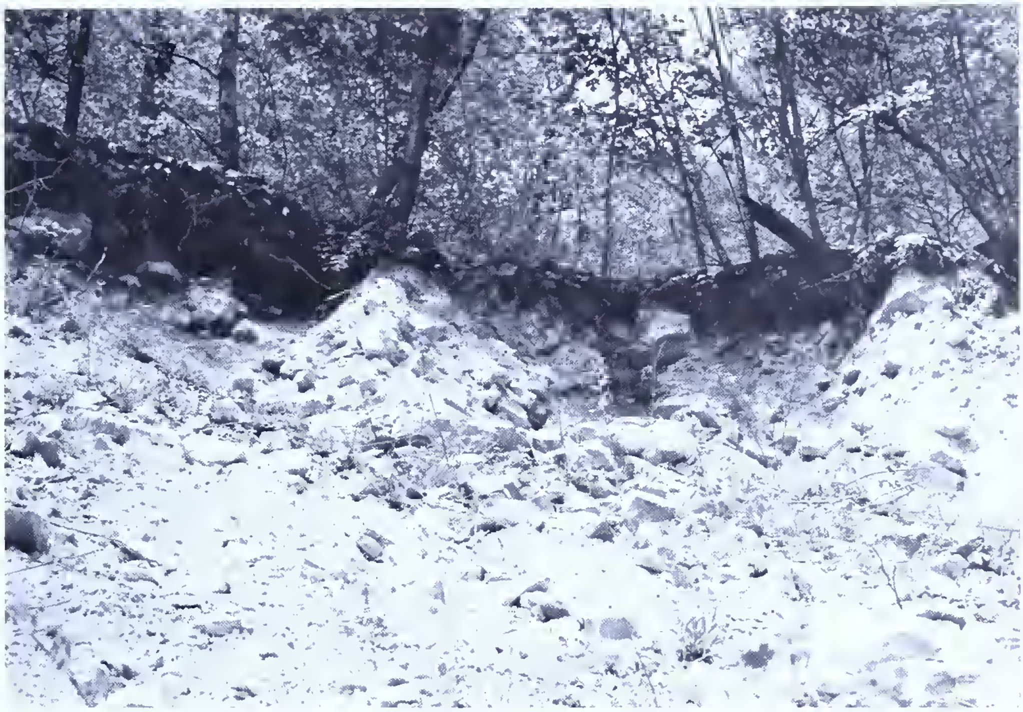


Figure 3. Rock creep. A steep, boulder- and rock-covered slope, down which rocks are slowly moving toward the toe. As this process takes place it can accelerate into rapid flowage. For example, the slope may become saturated from heavy precipitation and the movement may turn to a debris avalanche, resulting in rapid travel of material down to the bottom of the slope.

and therefore examples may be found throughout the state (Figure 1). However, like most gravity movements, rock creep may become stabilized under certain conditions, such as a dense accumulation of interlocking angular sandstone boulders (Figure 4). These outstanding features, seen in the Valley and Ridge province (Figure 1) on the steep slopes of narrow ridges and along the upland slopes of some water gaps, would at first appear to be ideal locations for the occurrence of natural rock creep. Although rocks occasionally move down these stabilized slopes, they are not prominent areas of natural rock creep. As long as the slopes remain undisturbed by works of man, the rocks generally stay in place, wedged one against the other, forming tight boulder nests of interlocking pieces which have apparent long-term stability. This stability is often enhanced by a lack of fine material in the spaces between boulders, thus allowing water to flow through and away from the boulder slopes, preventing the expansive force of freeze-thaw cycles.

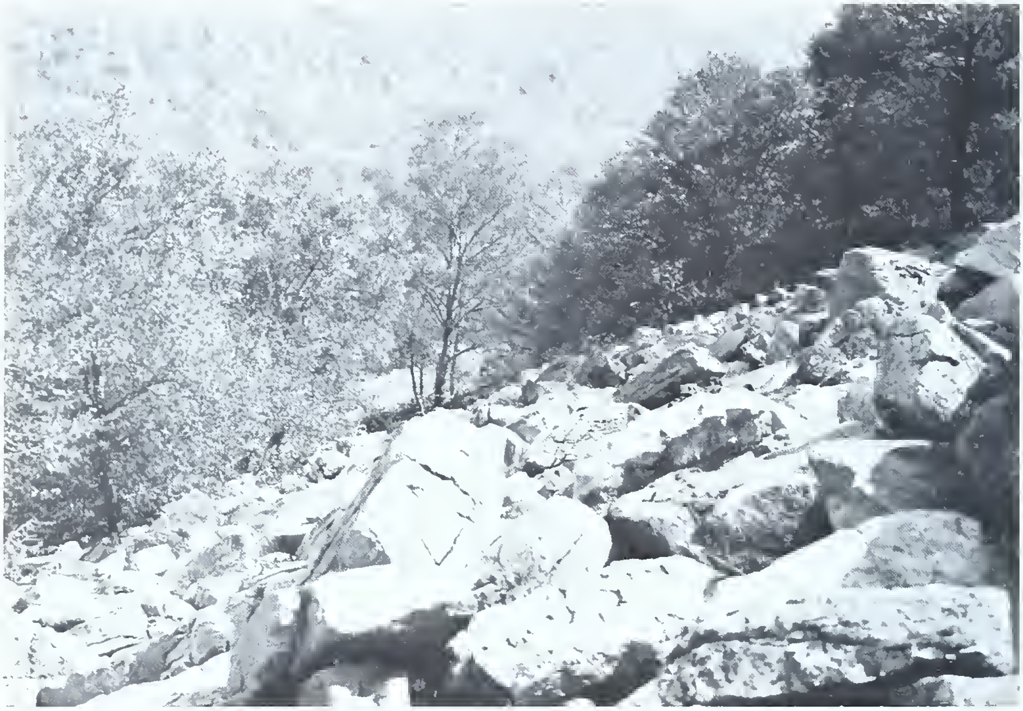


Figure 4. A dense accumulation of angular sandstone boulders forming a steep slope. As long as the slope is not disturbed, it commonly stays in a relatively stable condition because there are no small rock fragments and soil between the boulders and water drains freely from the hillside.

TALUS CREEP

Description

Talus creep is closely related to rock creep. Talus is coarse rock waste at the foot of a cliff or steep slope. It is loose rock rubble which has accumulated by weathering and rockfall from the slope above (Figure 5). If the surface on which talus accumulates is gentle, rock waste will build up as a wedge-shaped deposit. If the slope beneath the cliff is steep, which is often the case in Pennsylvania, rock waste will spread down across it in a sheetlike fashion. Wherever talus occurs there will be talus creep, and the same mechanisms that cause rock creep will be the active agents of movement.

The downslope movement of talus is augmented by loading at the top. Pieces that weather and fall from the steep slope settle near the top of the talus rubble and add impetus to downslope movement. Those pieces near the foot have a larger percentage of

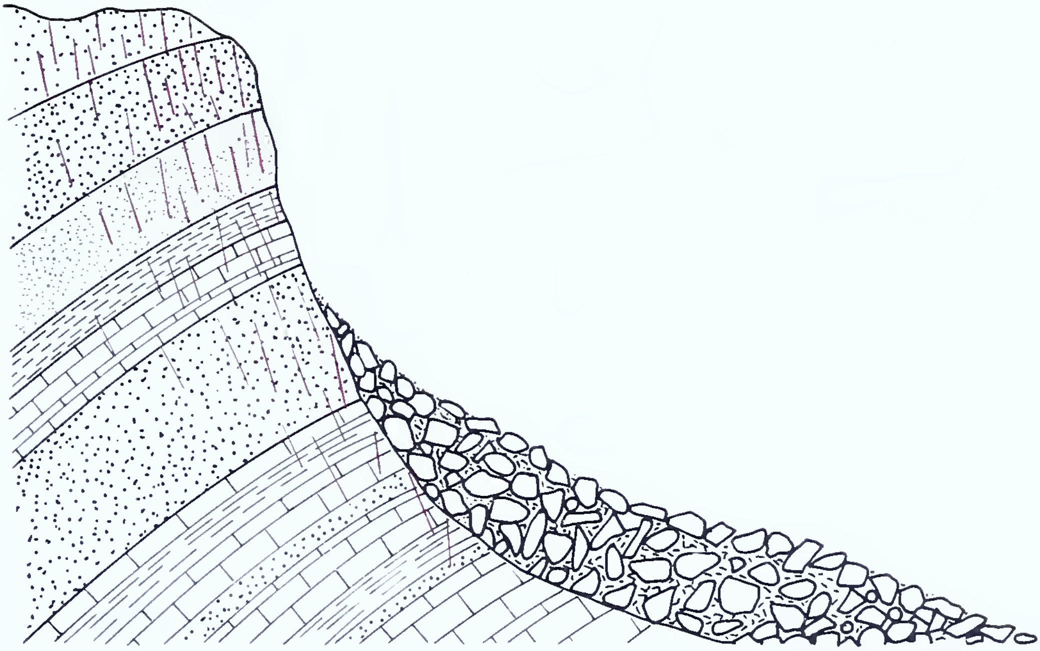
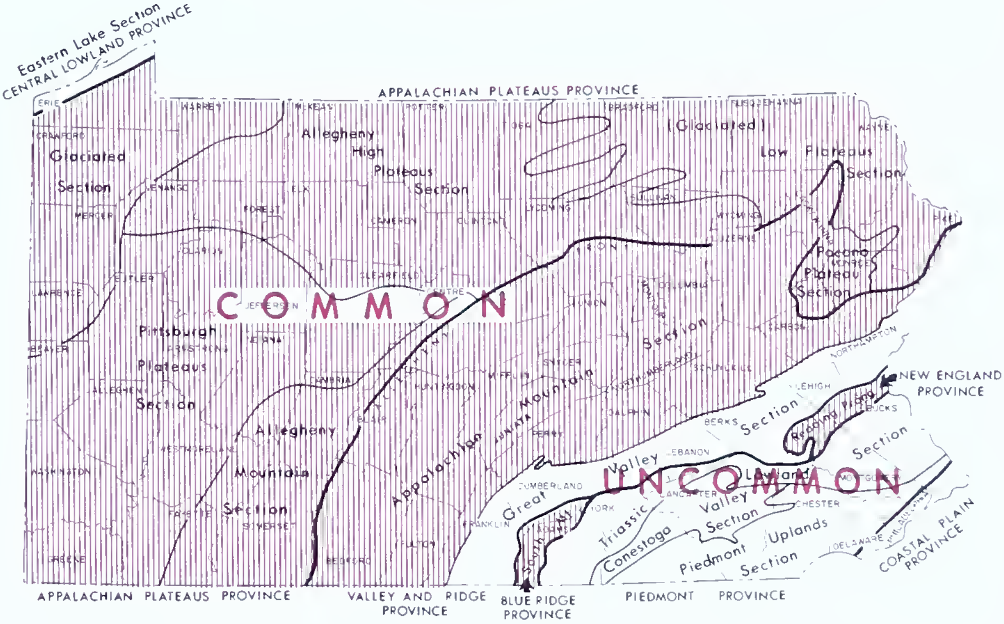


Figure 5. Weathering profile of a cliff face showing a talus slope at the foot of the cliff. Rock fragments break away along steeply dipping fractures, which are shown in red.

fine material mixed in and move downslope by rock creep, making way for blocks and pieces from above.

Occurrence



OCCURRENCE OF TALUS CREEP IN PENNSYLVANIA

Talus creep is less prevalent than rock creep but occurs throughout the state wherever there are cliffs or steep slopes. It is most prevalent in the Appalachian Plateaus province, the Appalachian Mountain section of the Valley and Ridge province, the Blue Ridge province, and the Reading Prong. It is uncommon in the Great Valley.

SOIL CREEP

Description

Soil in almost every soil-covered slope moves slowly downhill in response to gravity. The rate of soil creep depends upon steepness of slope, type of soil, moisture content, and climatic conditions; creep is active even on forested slopes. Surface evidence of soil creep is often quite noticeable. Tilted fence posts, fence rows displaced downslope, curved tree trunks, and turf rolls downslope are all common evidence of soil creep (Figure 6). Curved trees become concave upslope as the tree growth responds to downslope movement and bends to the source of light, usually becoming vertical

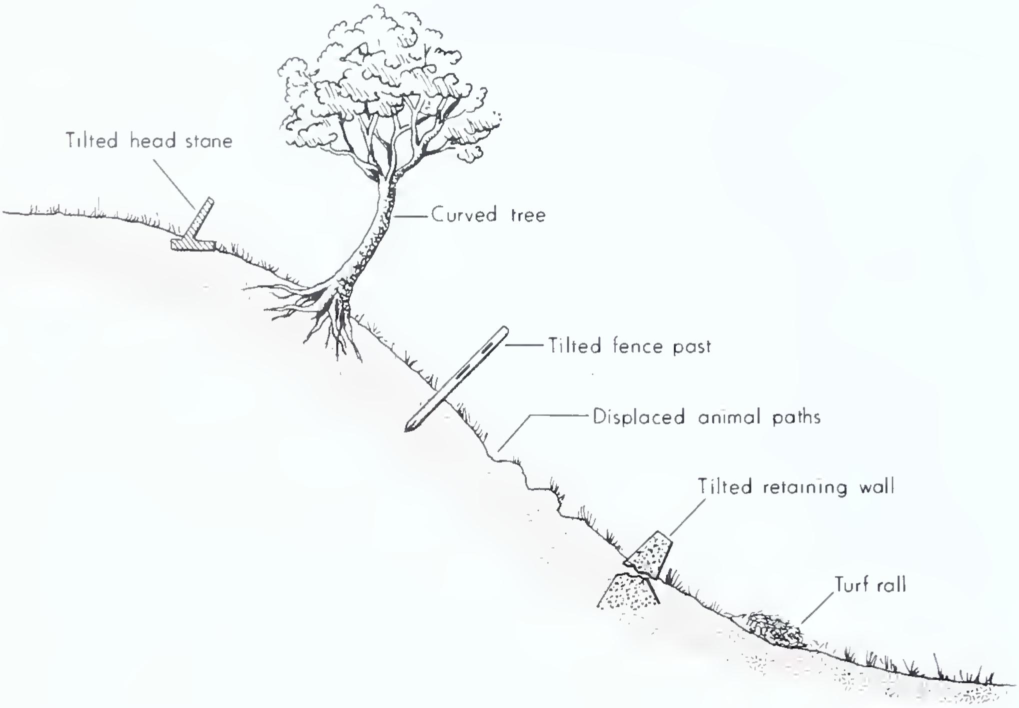


Figure 6. Recognition of soil creep by downhill displacement of trees, sod, paths, fence posts, and other man-made objects.

with time. The age of the tree and nature of the bend indicate the age of the movement.

The causes of soil creep are comparable to that of rock creep. Water infiltration and freezing and thawing play a major role in its occurrence, although other contributing factors also cause creep to take place. These other factors are: alternate heating and cooling in summer, providing greater expansion downhill; desiccation cracking when dry; moisture changes; wedging by growing plants; animal burrows; and chemical decomposition.

Results of the freeze-thaw cycle are apparent on many slopes. As moisture in the soil freezes, particles are lifted in a direction perpendicular to the slope. Then, as the ground thaws these same particles settle downward by gravity, coming to rest at a point lower on the slope. With this mechanism a layer of soil near the surface will move at a faster rate than the soil at greater depths. However, the slow flowage created has substantial motive force, and as surface layers are loosened, deeper layers are affected.

Soil creep may accelerate into rapid flowage when the water content of a soil is greatly increased or other conditions affecting slope stability are changed. Creep alone is not usually a serious geologic hazard (Figure 7) but it is capable of causing broken sewer

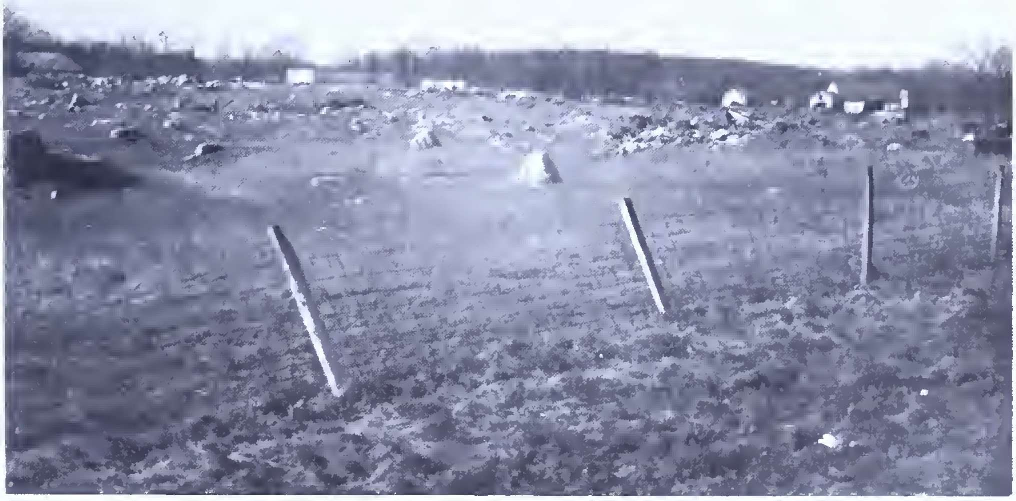


Figure 7. Soil creep on a gentle slope indicated by tilted fence posts.

and water lines. Creep may also lead to conditions that result in more drastic slope failure on potentially unstable hillsides.

Occurrence

Creep occurs on most slopes and is widespread throughout the state. However, on many hillsides it does not lead to catastrophic slope failure. In most cases where creep triggers more pronounced movement there is an underlying instability of the slope that exists because of its geologic setting. It is emphasized that not every slope in the commonwealth is subject to the occurrence of landslides, but rather "the external factors that initially created hillslopes" (Wyrwoll, 1977) have set the stage for downslope movement of hillside material in those areas where landslides occur.

EARTHFLOW

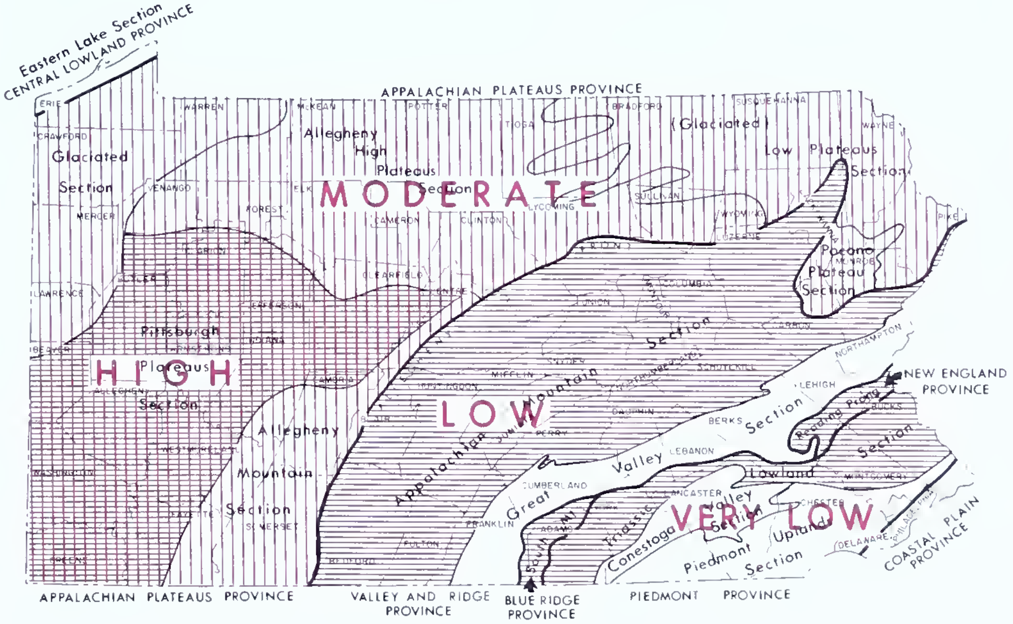
Description

Earthflow is a rapid, visible mass movement characterized by downslope flow of soil and weathered rock over a discrete basal surface. Bedrock movement is not involved. The basal surface is more or less parallel to the ground surface in the lower portion of the flow. There are generally three distinct parts of an earthflow: 1) a source area that has a headland scarp; 2) a central section of broken and disrupted soil that has open fissures across the flow; and 3) a lower section of raised hummocky ground. Earthflow is the slowest moving of the three types of rapid flowage that occur in Pennsylvania.

Conditions of earthflow are variable but are most favorable where there is saturation of thick soil atop an impermeable bedrock surface or clay layer. Water from the surface is slow to move through the barrier beneath the soil, resulting in a saturated soil overburden that is capable of earthflow and slope failure even on a gentle incline.

Occurrence

Earthflow is an aggravating problem in western Pennsylvania, being most prevalent in areas where the bedrock consists of the *Pittsburgh red beds* along the sides of major stream valleys. Recently mapped areas of western Pennsylvania (Pomeroy, 1976) show a regional distribution of earthflow. Mapping this feature must necessarily be done at a scale that shows detail, because an area of an acre or so that is prone to earthflow is often adjacent to land that can be considered stable. It is, therefore, necessary not to over generalize by saying an entire region is prone to slope failure, but to define problem areas by detailed examination. Most natural earthflow slope failure in Pennsylvania occurs in specific areas of the Appalachian Plateaus province; there are far fewer occurrences in the Appalachian Mountain section of the Valley and Ridge province and the Blue Ridge, Reading Prong, and Triassic Lowland provinces. The highest concentration of natural earthflow is in the Pittsburgh Plateaus section of the Appalachian Plateaus province.



OCCURRENCE OF EARTHFLOW IN PENNSYLVANIA

Figure 8 is a photograph of an earthflow showing the well-defined lateral boundaries, the headward scarp, and the hummocky ground and lobes at the toe. Earthflow is often intermittent, and periodic downslope movement may occur for several years after the initial failure.

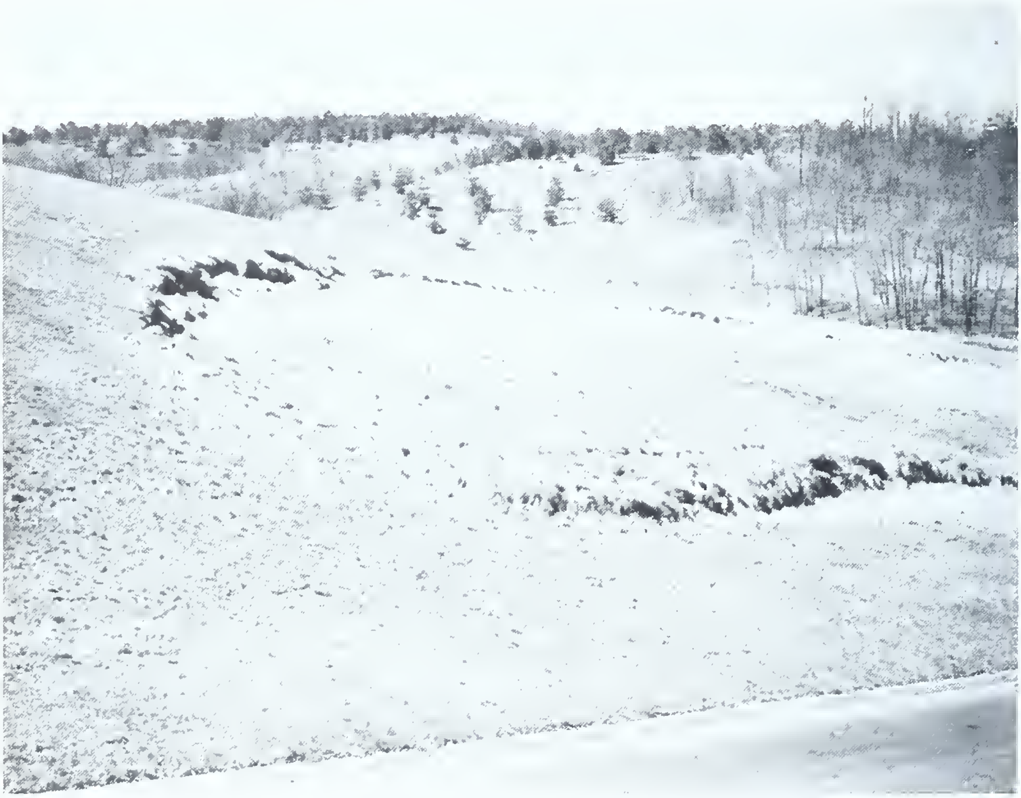


Figure 8. Earthflow characterized by downslope movement of wet soil that acts as a thick, viscous fluid (photograph by J. L. Craft).

MUDFLOW

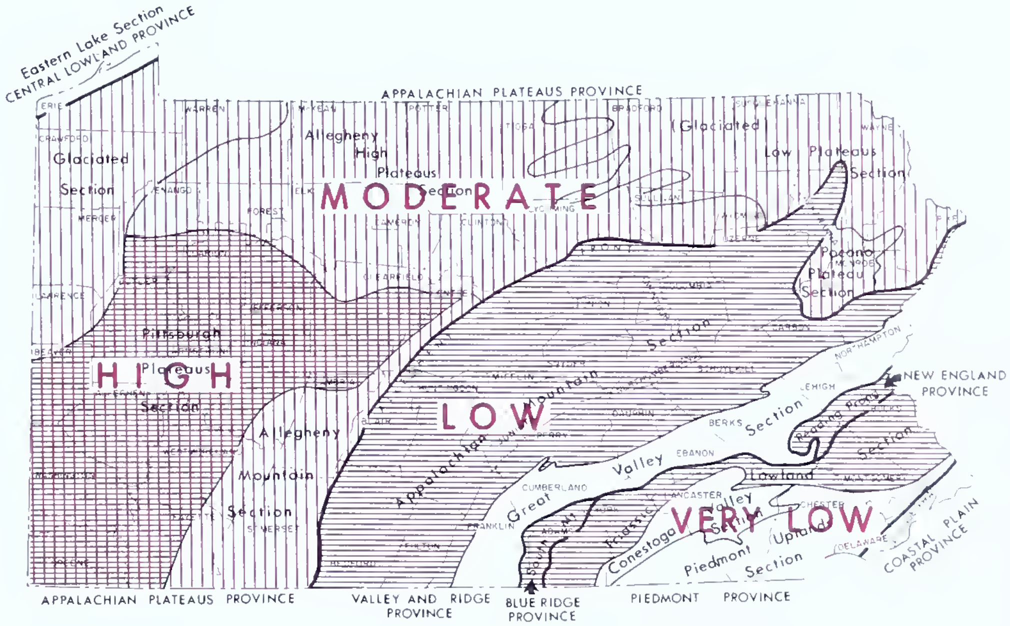
Description

A mudflow may be likened to a muddy river, except that in the mudflow there is somewhat more solid matter than water. A mudflow can involve considerable amounts of debris and large blocks of rock which are carried along on a sometimes gentle surface by the force of flow. Mudflows are generally associated with short periods of heavy precipitation and runoff occurring in established stream channels that are partially filled with soil and debris.

Occurrence

Mudflows occur in areas of Pennsylvania where vegetation has been removed from slopes, followed by heavy rain. The water saturates the soil and, when the mixture becomes sufficiently fluid, a mudflow develops. Mudflows are not naturally common in Pennsylvania because the humid climate does not allow significant accumulation of fine material. Nevertheless, occasional mudflows do occur. These flows occur in areas of considerable relief in the state.

Mudflow potential localities are characterized by an absence of substantial vegetation and the presence of deeply weathered soil. Such conditions are most likely to be associated in Pennsylvania with the works of man in construction, agriculture, or mining.



OCCURRENCE OF MUDFLOW IN PENNSYLVANIA

DEBRIS AVALANCHE

Description

A debris avalanche (Figure 9) is a type of rapid mass movement involving a major portion of coarse material. It is the sudden, rapid downslope flowage of completely water saturated soil and rock debris, producing a long, narrow scar on the slope where it occurred and an accumulation of the material at the toe. Unusually long and heavy rain is the triggering mechanism that initiates a debris avalanche at a point of instability.

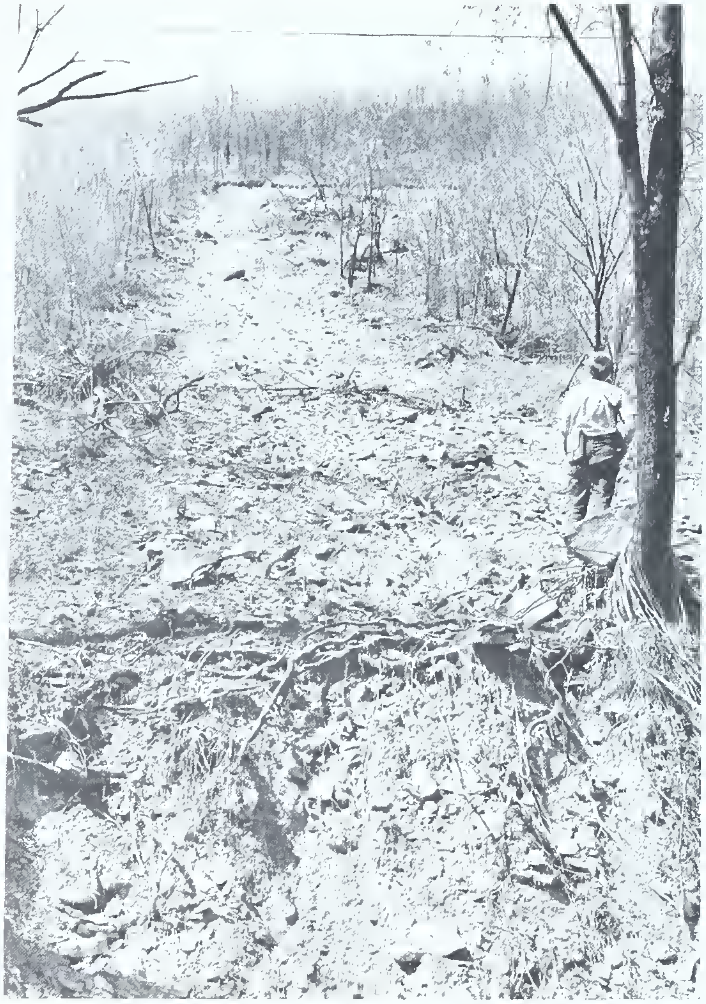


Figure 9. A debris avalanche that made a long, narrow path as loose rock, soil, and trees moved rapidly down a steep hillside.

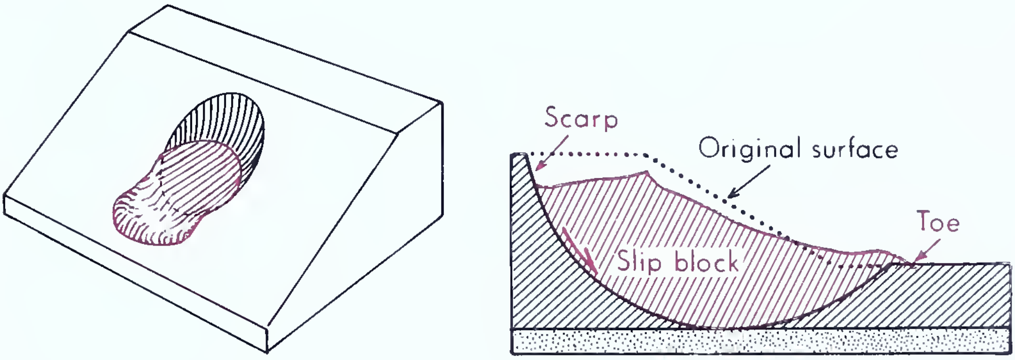
Occurrence

Debris avalanches do happen occasionally in Pennsylvania; most recently there have been a number of occurrences associated with Hurricane Agnes (1972) on the flanks of ridges in the Appalachian Mountain section of the Valley and Ridge province, and in the Appalachian Plateaus province associated with heavy rain in the Johnstown area in 1977. Debris avalanches, however, are more common on the high, glaciated mountains of New England and in the Blue Ridge Mountains of the southeastern United States, where there is a thick residual soil lying on a sloping bedrock surface.

SLUMP

Description

Slump is downslope sliding of rock or unconsolidated material moving as a unit, characterized by rotary movement along a curved slip surface; the rotation of the moving mass is around an axis parallel to the slope from which it descends. There is a backward tilting of the slumped mass toward the slope, and the formation of a scarp at the top and a bulge at the toe (Figure 10). The surface of rupture and slippage is curved upward, concave toward the slip block, and the movement is rotational through a relatively homogeneous mass. Slumping results primarily from a removal of support at the toe of a potential slip block, caused by erosion farther down the slope, or by man-made cutting away of support. This type of failure commonly occurs in soil and weathered rock on hillsides where there are no planar discontinuities, but may also involve bedrock.



Spoon-shaped slope failure (after Varnes, 1958)

Slump in homogeneous material

Figure 10. Internal movement and generalized configuration of the surface of rupture characteristic of slope failure.

Occurrence

Slump and slumping in combination with other types of landsliding are common in western Pennsylvania and occur to some extent on many hillsides throughout the state. Most common is slump along stream banks (Figure 11); the flowing river water undercuts the banks, allowing the ground above to slide down

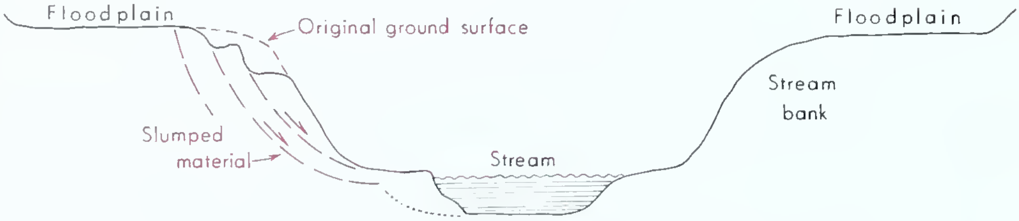
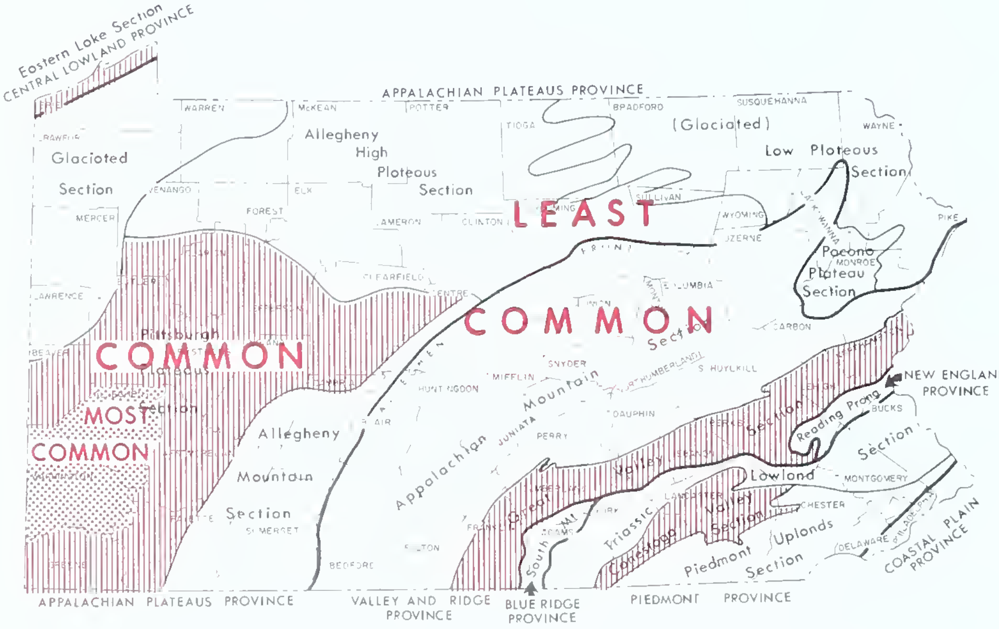


Figure 11. Common slumping along a stream bank.

along crescent-shaped failure surfaces, pushing material into the flowing water. Erosion at the toe is accelerated, often allowing slump and related movement in the stream bank to continue.

Slump failure is most common on hillsides in Allegheny and Washington Counties, and has been the cause of significant property damage. It is associated there with instability of soil and weathered rock from the decomposition of underlying shales and clays in rock sequences that include the western Pennsylvania coal formations.



OCCURRENCE OF SLUMP IN PENNSYLVANIA

Slump is also a notable occurrence in the Great Valley section of the Valley and Ridge province, where broad areas of limestone bedrock often are overlain by a thick residual clay soil that is susceptible to slumping.

Bluffs along the shore of Lake Erie in northwestern Pennsylvania fail by periodic slumping.

Slump failures may be relatively small, involving several tens of cubic yards, as illustrated in Figures 12 and 13, or they can be large, complex, rotational slope failures (Figures 14 and 15).

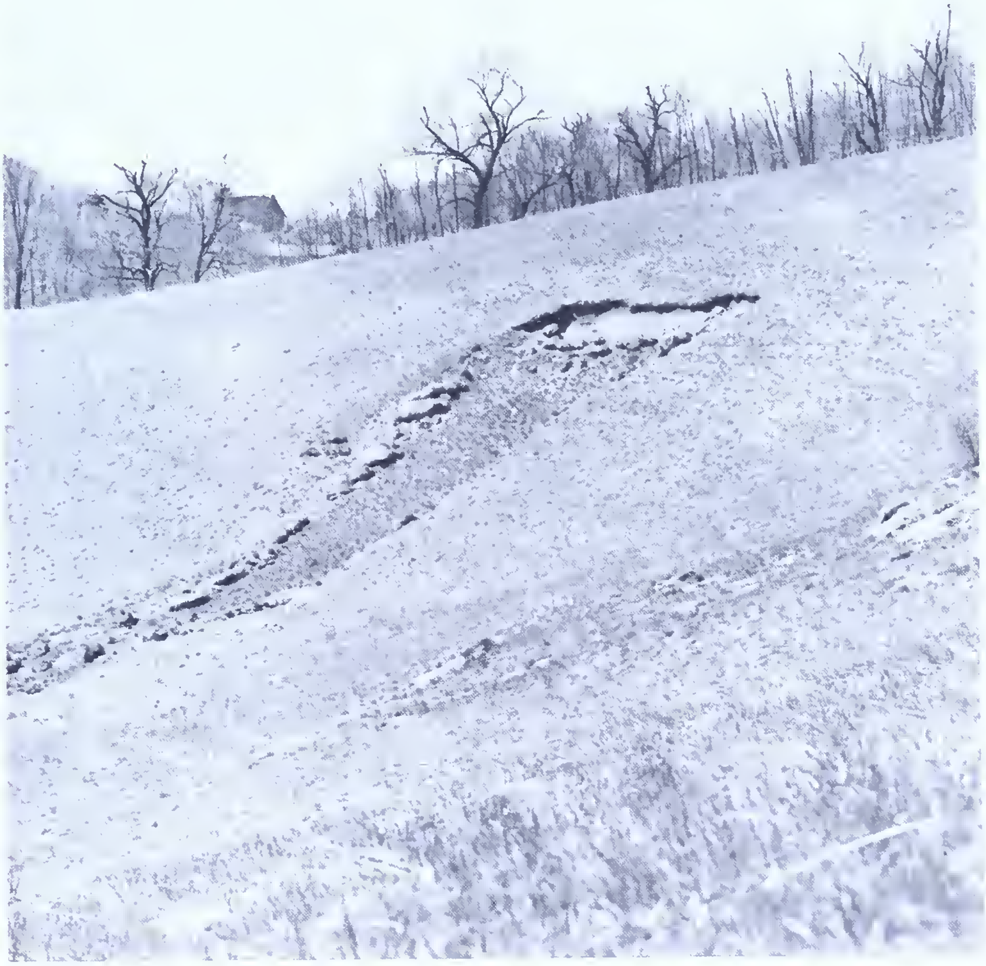


Figure 12. Hillside slumping. The toe of the slump has tumbled farther downhill as a debris avalanche.

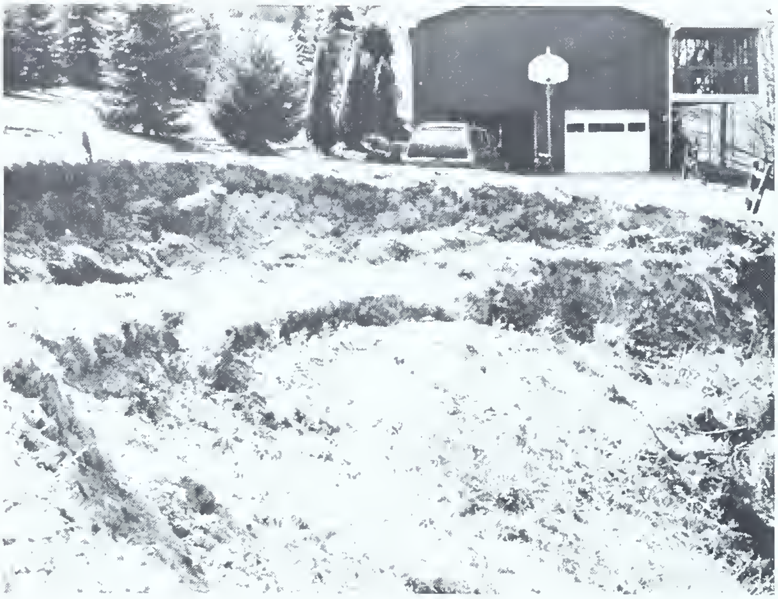


Figure 13. Slump failure illustrating a steep scarp at the head above the disrupted ground (photograph by R. P. Briggs).

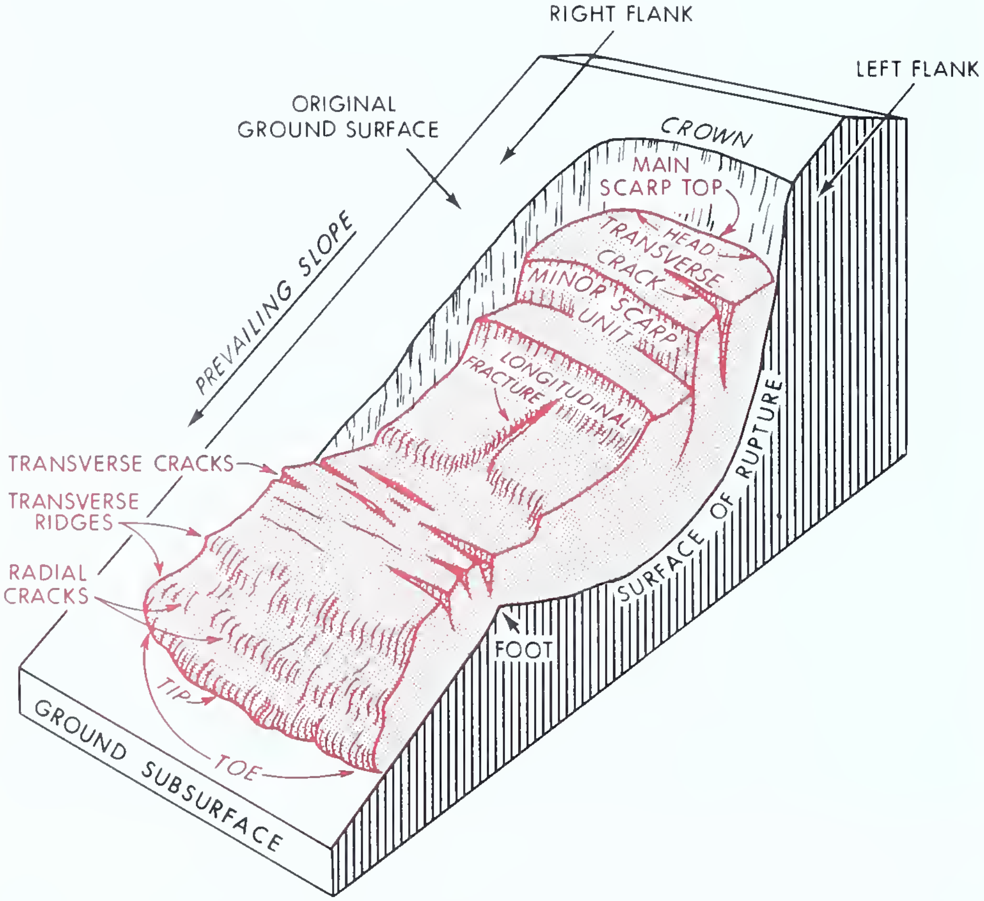


Figure 14. Elements of massive, complex slump failure (after Varnes, 1958; original drawing by G. Ladwig).

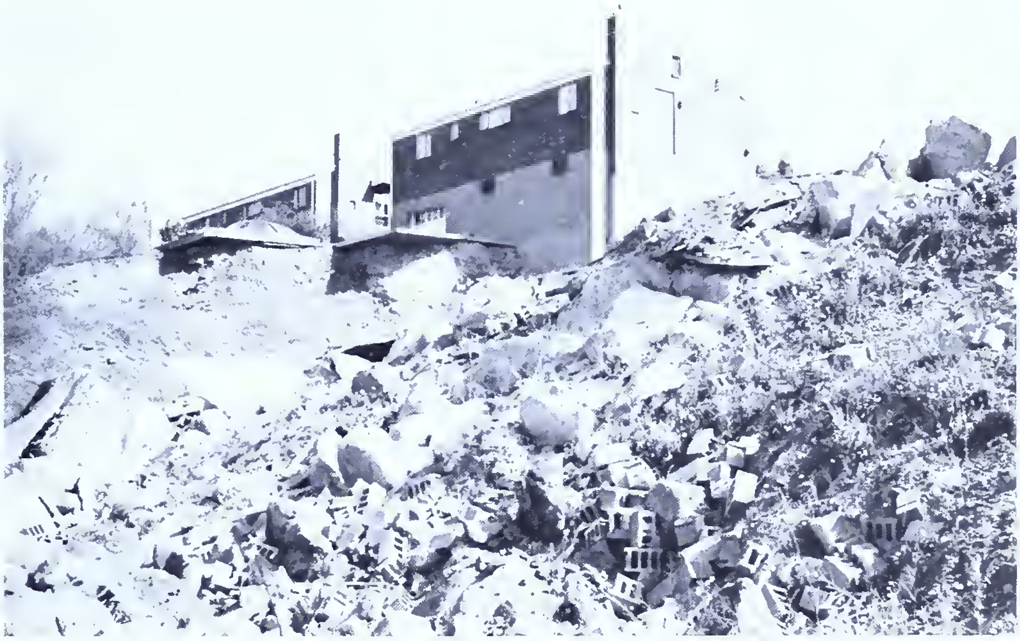


Figure 15. Slope failure that has involved slumping at the toe of the slide.

DEBRIS SLIDE AND DEBRIS FALL

Description

Debris slide is the rapid, downward movement of predominantly unconsolidated and incoherent earth and debris in which the mass slides forward, ending up as an irregular, hummocky deposit. Debris fall is the relatively free-falling of predominantly unconsolidated earth and rock debris from a vertical or overhanging cliff. In these types of sliding, the surface of movement is generally a bedding-plane surface, a joint surface, or the surface marking the top of the bedrock. The basic point is that in these slides, the whole sliding mass moves as a unit.

Recognition of common debris sliding is illustrated in Figure 16. The soil and weathered rock typically move slowly downslope by creep to a point at which the slope increases in steepness. A debris slide results as the material approaches the edge and slides down. If the slope is vertical, the resulting mass movement will be debris fall. If there is no increase in slope steepness, the mass of accumulating material can still slide if there is lubrication of the bedrock surface by water.

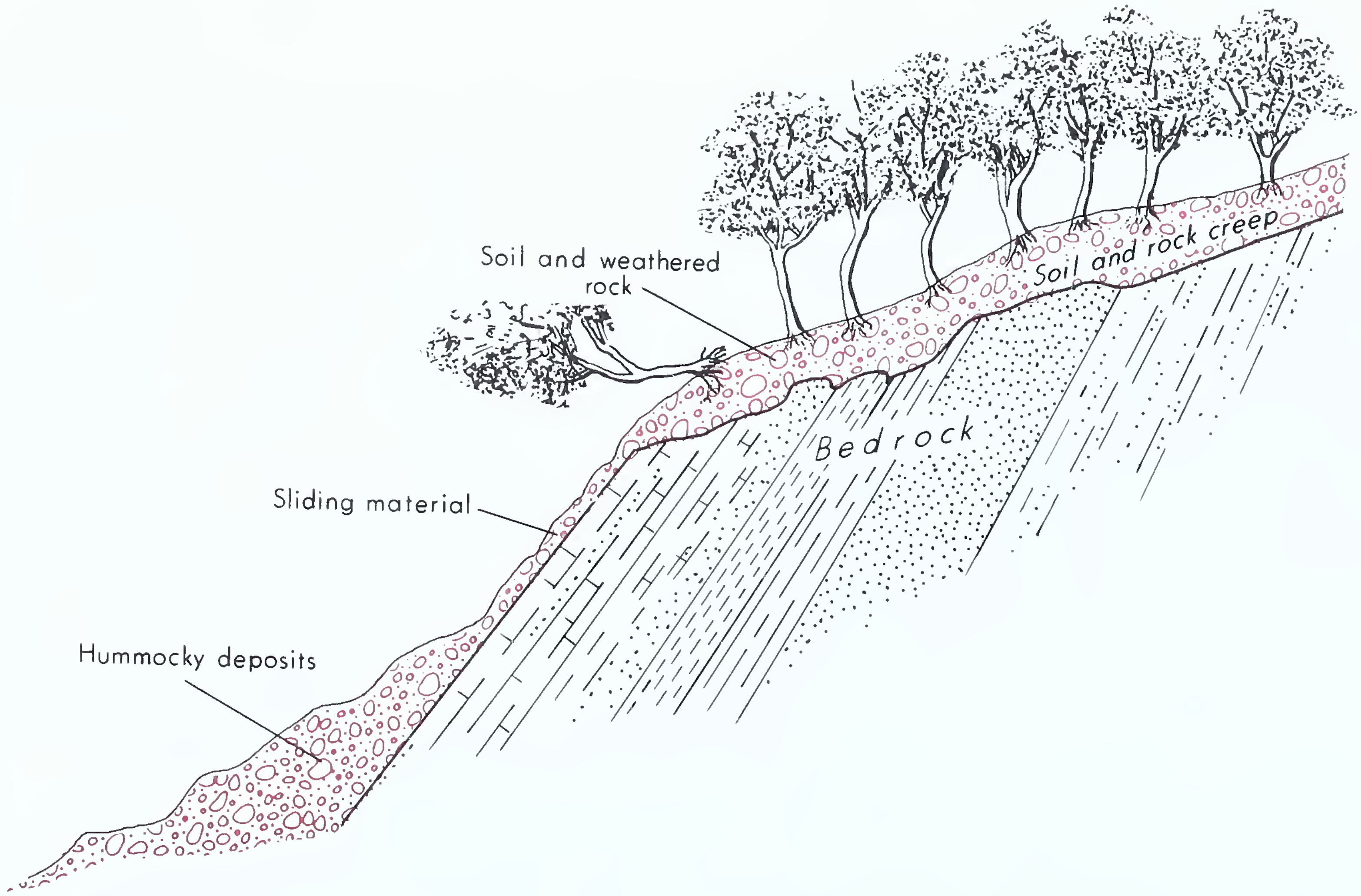


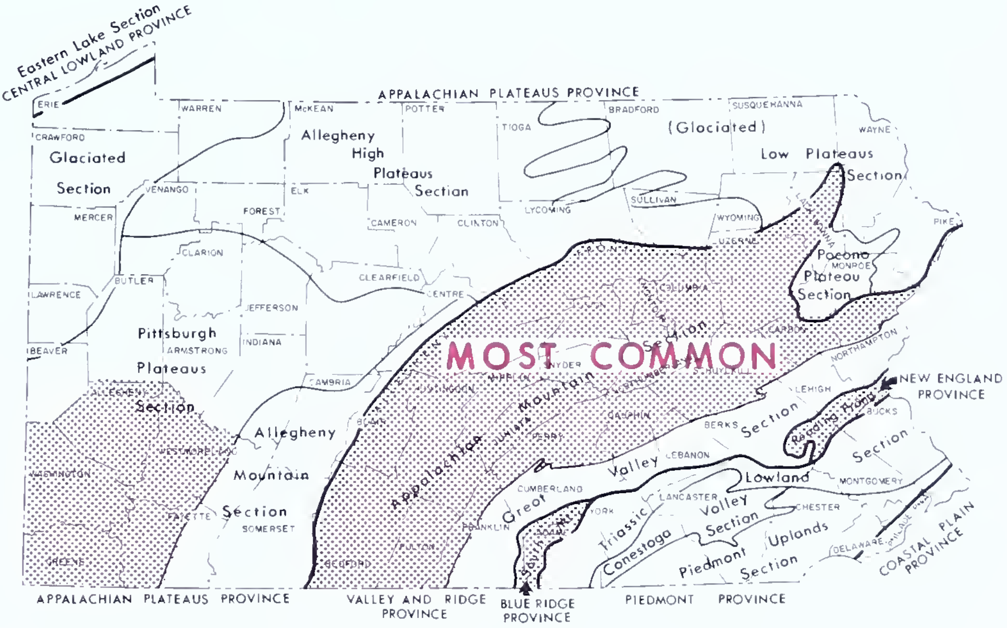
Figure 16. A debris slide along a steeply inclined bedrock surface. Material moves slowly to the edge by creep along the upper slope and periodically slides down the steep slope, coming to rest as accumulated debris in a hummocky deposit below.

Occurrence

Debris slides and debris falls, either individually or in combination, are common in many areas of Pennsylvania. These mass movements, in conjunction with rocksliding and creep, are representative of the weathering process that has caused the accumulation of extensive deposits of colluvium along the flanks of mountains and ridges in Pennsylvania (Figure 17).

The text of the *Preliminary Landslide Overview Map of the Conterminous United States* (Radbruch-Hall and others, 1976) notes ". . . The flanks of the Appalachian ridges and the Blue Ridge, especially those formed on sandstone and metamorphic rocks, are covered by extensive colluvium and scree deposits which are highly susceptible to sliding. Most of the abundant slope movement in the colluvium consists of slowly moving debris-slides. . . ."

Much of the slope failure that is common to southwestern Pennsylvania moves as a debris slide during at least part of its downslope travel.



OCCURRENCE OF DEBRIS SLIDE AND DEBRIS FALL IN PENNSYLVANIA

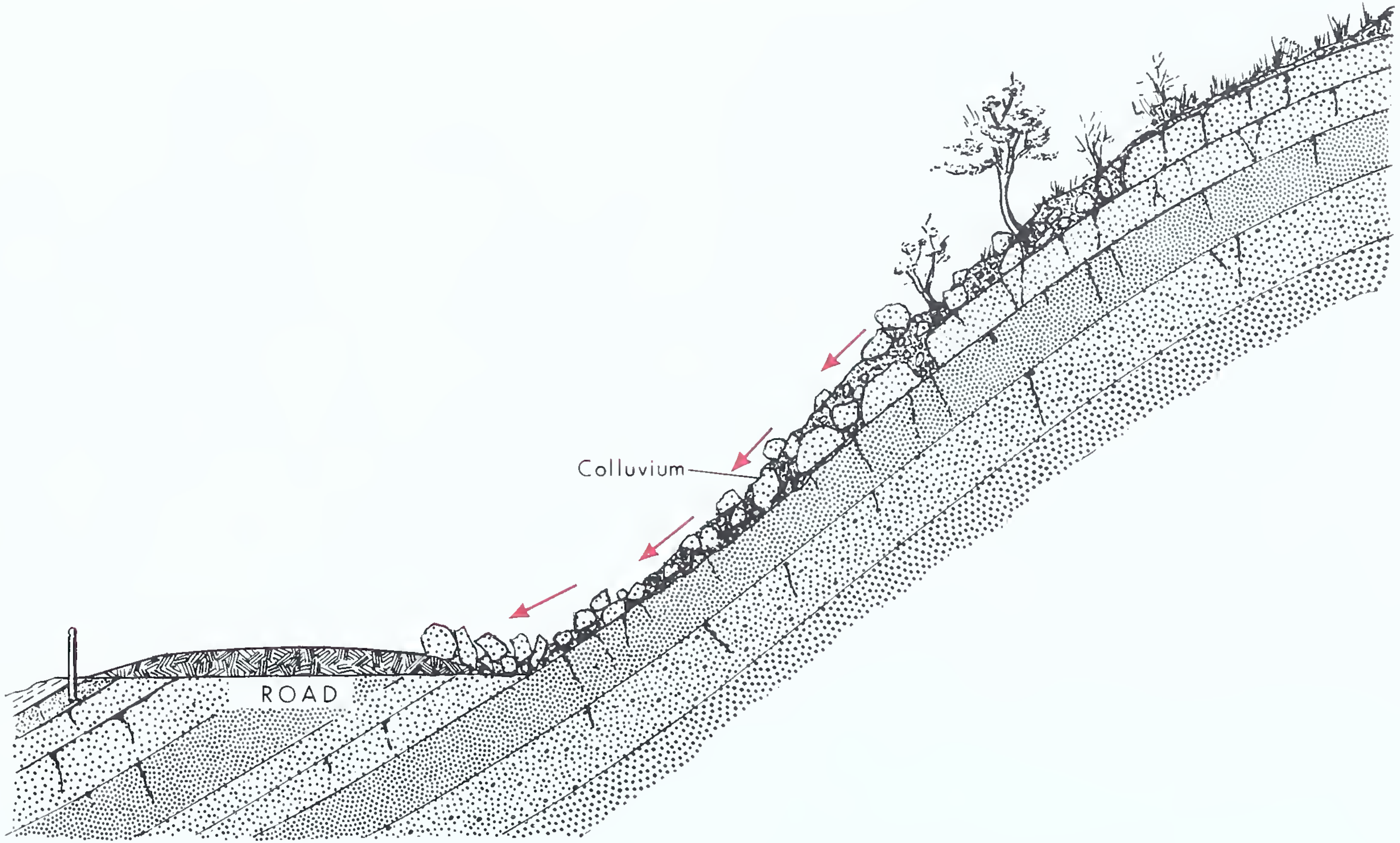


Figure 17. A debris slide and rockslide in blocky, steeply inclined sandstone.

ROCKSLIDE

Description

Rockslide is the downward and usually rapid movement of newly detached segments of bedrock sliding on bedding, joint, or fault surfaces or any other surface of separation. Most rocksliding in Pennsylvania is along a plane surface, as illustrated in Figure 17. There are a number of bedrock characteristics that determine the susceptibility of a hillside to sliding. Significant characteristics are 1) the position of bedding, joint, and fault surfaces with respect to the hillside slope, 2) the extent of weathering and soil-mantle thickness, and 3) water-filled fractures in the rock.

Hard rock, such as brittle sandstone, that is broken along fractures and bedding planes is a rock type subject to rocksliding on natural or manmade slopes. Shales also are good examples of rocks that exhibit rocksliding on slopes. Where the dip of the bedding planes and fracture surfaces is in the same direction but less steep than the dip of a slope surface, rocksliding can readily occur. A rock slope subject to considerable weathering can have a large amount of loose rock built up on it, and this load will eventually result in rocksliding.

One of the main triggering agents of slides is increased water content acting as a lubricant along potential slide surfaces. In Herndon, Northumberland County, for example, a rockslide and debris slide took place at night during the heavy rains of Hurricane Agnes in June 1972, killing one person and destroying three homes and a highway.

Increased water alone, however, is not the only initiating factor. There is generally a relatively weak, incompetent rock layer present on top of an impermeable layer through which percolating water will not pass, so that there is a saturation of the potential slide material. This is illustrated in Figure 18, which shows a typical example of areas of potential rockslide in southwestern Pennsylvania. A relatively thick, fractured sandstone and shale bedrock overlies carbonaceous shale and claystone. There is a gentle dip of the bedrock toward the slope face. Water from rain or melting snow can percolate down through the sandstone and shales relatively easily, but percolation through the fine-grained dense claystone below is slow. In addition, the very fine grained nature of

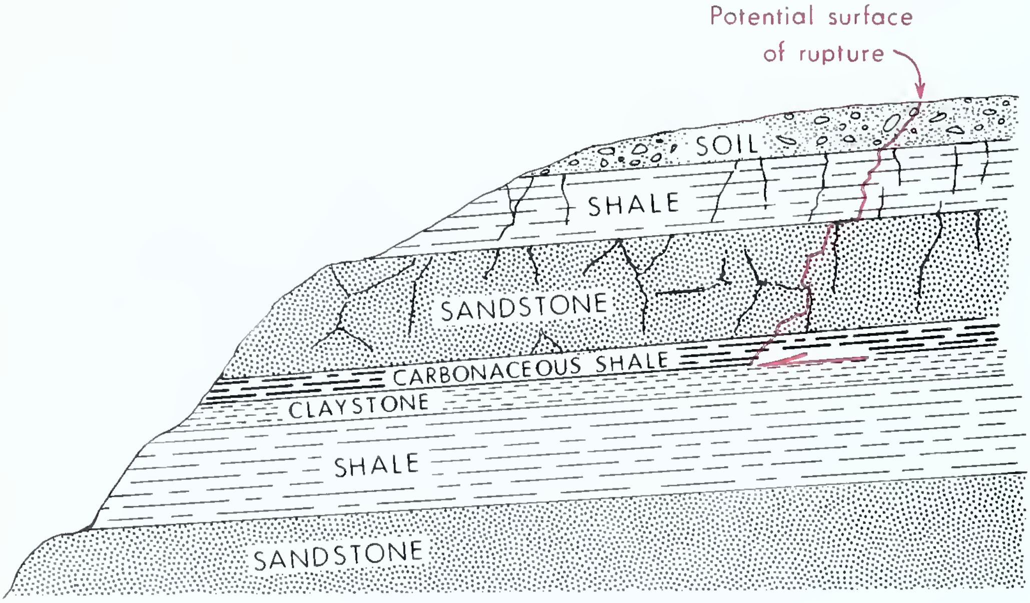


Figure 18. Slide-prone bedrock. The thick sandstone and shale is subject to rockslide along a surface of rupture at the top of the claystone. The bedrock dips gently toward the slope face.

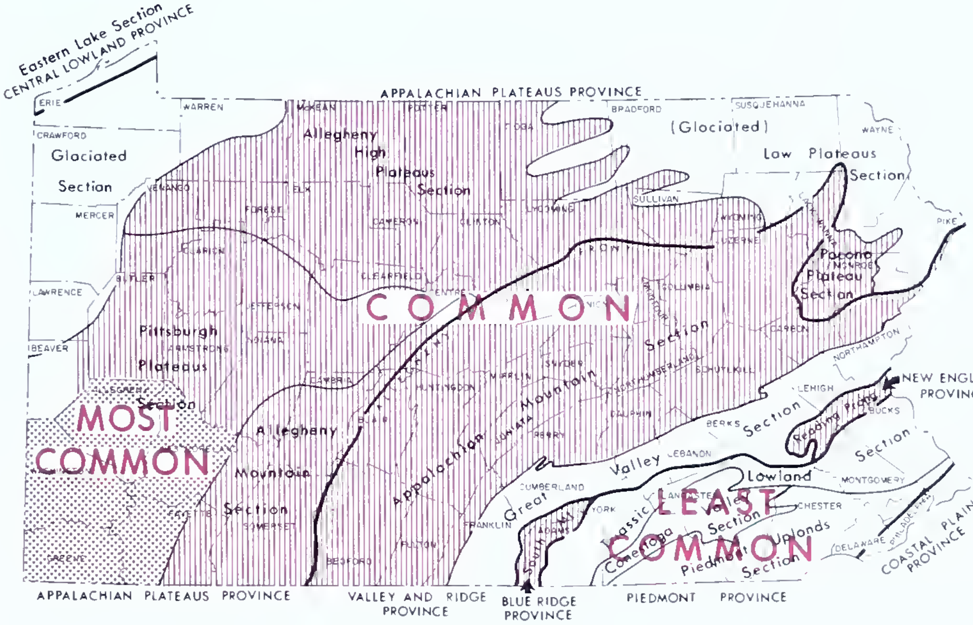
claystone makes it slippery when wet. Therefore, as groundwater saturates the rock units above the claystone, water pressure increases in the pore spaces in the rock and concentrates at the top of the claystone, setting up a potential surface of slippage. Now any triggering agent, such as a vibration or sudden increase in precipitation, will allow all of the water-saturated rock above the claystone and near the slope to break away and slide suddenly toward the valley.

Occurrence

Prominent rockslides and related phenomena of southwestern Pennsylvania are noted in the text of the preliminary landslide map of the United States (Radbruch-Hall and others, 1976): "The most extensive area of unstable rock in the eastern United States is in the Plateaus province of the western part of the Appalachian Highlands where numerous landslides have developed in the coal, claystone, shale, limestone and sandstone bedrock. The shales, especially the red beds and shale-limestone sequences, disintegrate into clay rapidly upon exposure. Landslides in the weathered rocks are very common; over 75 percent of the slopes in the area from Pittsburgh south show signs of failure. Although most of the slides involve weathered bedrock, they are shallow, generally less than 5 feet thick. Commonly the material moves as a slab at the rate of a foot or two per year or less. . . . Damages run into many million dollars per year."

Exposure of bedrock units is greater along the valley sides of major rivers that have cut into the relatively flat lying rocks of the plateau than it is in some lesser valleys. The potential for rocks to slide in these larger valleys is therefore enhanced, and in one case the great number of slides that has occured in the past has given a river its name. Monongahela is the American version of an Indian name Menaungehilla, which means "high banks breaking off and falling down in places" or, as the Monongahela was apparently called, "river with the sliding banks." In western Pennsylvania, however, the history of slope failure and the potential for failures along secondary valleys far exceeds, in total, the failures along the major rivers.

A combination of rockslide and rockfall is not unusual in the Plateaus province where soft, easily eroded shales are overlain by more resistant sandstone or siltstone (Figure 19). The thick shale, illustrated in the sketch, near the base of the steep hillside will erode and undercut more resistant units, removing support from beneath them and allowing them to fall or slide to the toe.



OCCURRENCE OF ROCKSLIDE IN PENNSYLVANIA

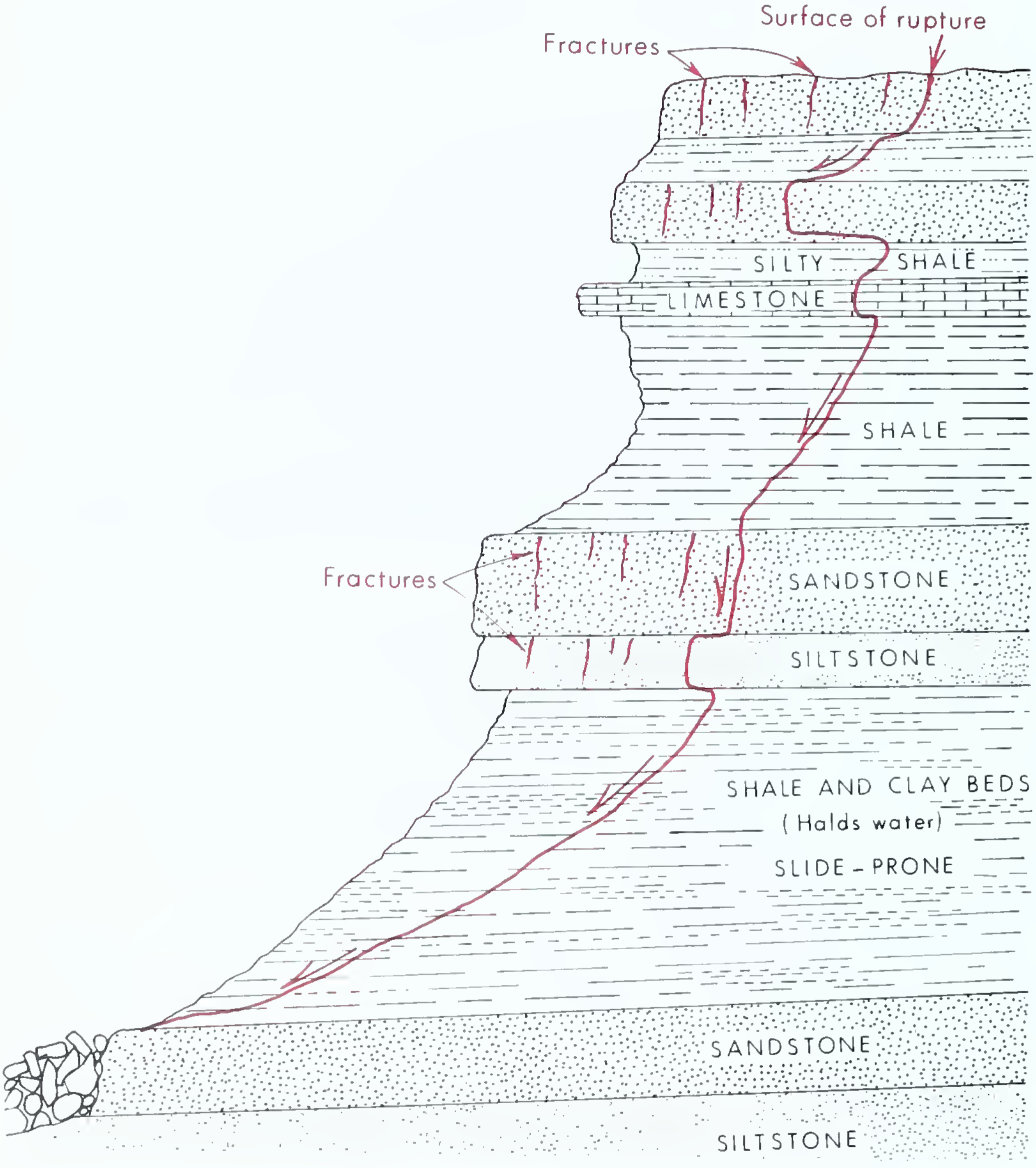


Figure 19. A hillside roadcut in the Pittsburgh Plateaus section of the Appalachian Plateaus province. The shale and clay units are susceptible to undercutting and rapid weathering, which results in slumps, rockslides, and rockfalls.

Other occurrences of natural rockslide are relatively common to the Appalachian Mountain section of the Valley and Ridge province, the Pocono Plateaus section of the Appalachian Plateaus province, the Blue Ridge province, and the Reading Prong.

ROCKFALL

Description

Rockfall is the free-falling of a newly detached unit of bedrock of any size from a cliff, steep slope, cave roof, or rock arch. Rockfall can be a single event or a series of single, intermittent events over a considerable period. Rockfall is most active in the spring after freeze-thaw cycles have loosened pieces of rock along joints and bedding-plane fractures, allowing them to fall down a steep, water-saturated slope or wet cliff face (Figure 20).

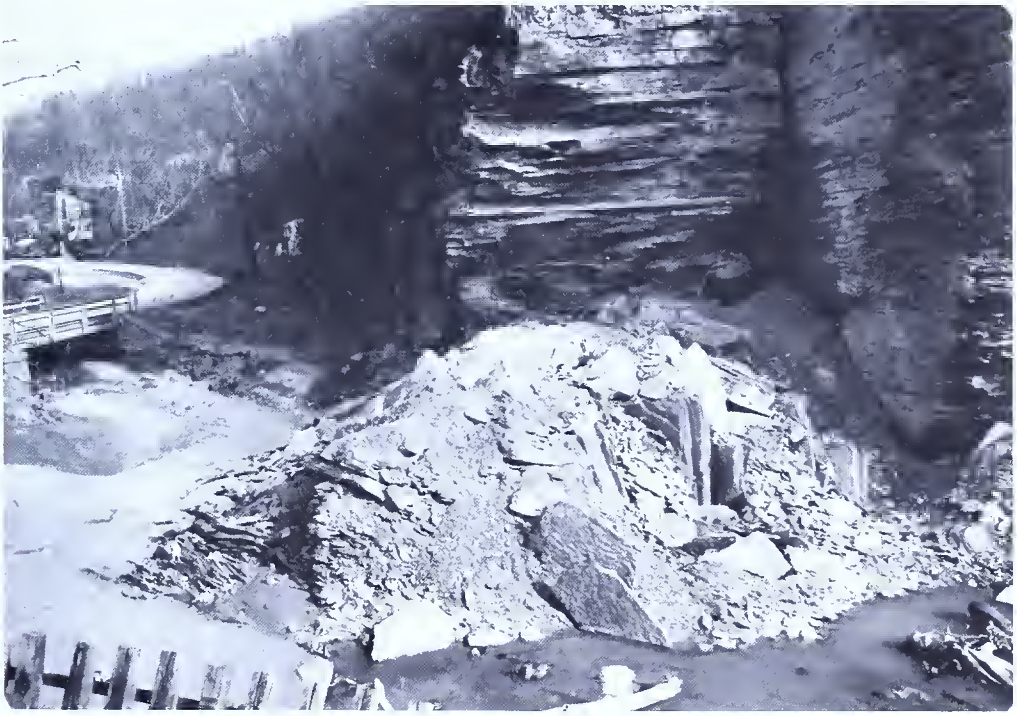
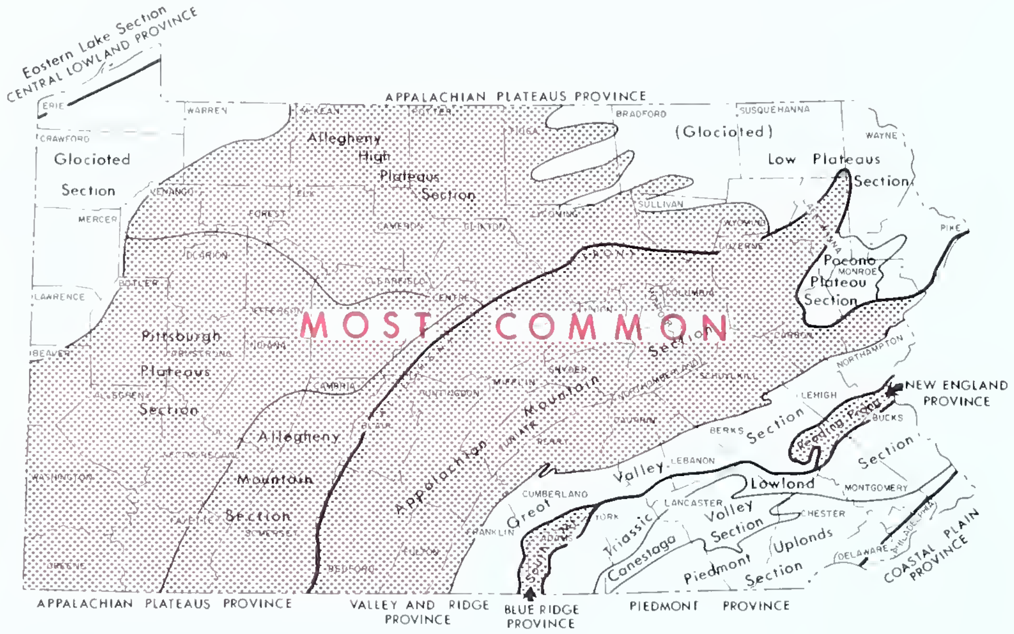


Figure 20. Rockfall from a cliff face into a stream channel. Note how the rock has fallen away along near-vertical joints, forming fresh cliff faces (photograph by J. L. Craft).

Occurrence

Rockfall from cliffs contributes to the accumulation of rock at the head of a talus slope and occurs most prevalently in mountainous areas of the state, which are the Appalachian Plateaus prov-



OCCURRENCE OF ROCKFALL IN PENNSYLVANIA

ince, the Appalachian Mountain section of the Valley and Ridge province, the Blue Ridge province, and the Reading Prong.

Natural arches from which rock may fall are notable in the Appalachian Mountain section of the Valley and Ridge province, where two outstanding examples are Arch Spring in Blair County and the entrance to Alexander Caverns in Mifflin County.

Rockfall is most common where streams and rivers have cut steep-walled valleys in bedrock as well as in man-made excavations. Every physiographic province except the Coastal Plain in extreme southeastern Pennsylvania has streams flowing at the base of cliffs along their courses. Under these conditions, water erosion can undercut the rock and set the stage for rockfalls.

MAN-INDUCED LANDSLIDES

Naturally occurring stability can be altered by the works of man, causing slopes to fail. For example, man's activity in construction and mining can cause an otherwise stable hillside to become unstable and to be subject to failure by a natural triggering event, such as heavy precipitation, or by a man-made triggering event, such as a blast.

In the last 200 years of building roads and excavating for foundations in Pennsylvania, geologic conditions have changed very little, but our technology has changed considerably. Large excavating machinery has been developed (Figure 21) that can take massive slices from hills and mountains. Tractor-scrapers used in highway construction commonly carry 30 cubic yards of soil and overburden. Large front-end loaders fill trucks with up to 50 tons of blasted rock and boulders. Before this ability to move mountains, man-induced landslides were not as great a problem as they are today because man tended to conform to the existing topography. Even though careful engineering investigation goes into the design of most roads and the foundations of most structures, all too often, conditions in soil and rock turn out to be different than had been recognized before construction began. On some projects, regretably, geologic conditions are not recognized or evaluated properly.

When children make cuts in play sand piles with toy bulldozers and graders, the results are often slides and slumps of loose, sandy material, interrupting the travel of Lilliputian armies along "homemade roads." The material on which real roads and highways are built is, in places, just as unstable as the sand pile of the sandbox. Fractures in bedrock, unfavorable groundwater conditions, improper angle of cut, and the nature of material being excavated can all contribute to an unstable situation when a hill is cut or a valley is filled to make way for a highway or a building foundation.

Man-induced landslides that are most often seen are in roadcuts in the hillside. Although the angle of slope of modern roadcuts is generally designed with slide prevention in mind, there are, all too often, unexpected conditions, such as an unknown concentration of groundwater flow that triggers flowage or sliding in what was thought to be stable ground. Virtually all types of landslides from creep to rapid flowage to rockslide and rockfall may be observed and studied along Pennsylvania's highways. Many are minor failures requiring little or no special maintenance, whereas others are massive failures which interrupt completion of construction or temporarily close a road to traffic. On a new four-lane highway under construction in Blair County, for example, 250,000 cubic yards of mountainside slid rapidly onto a completed portion of roadway. The cost to remove it was more than $300,000.

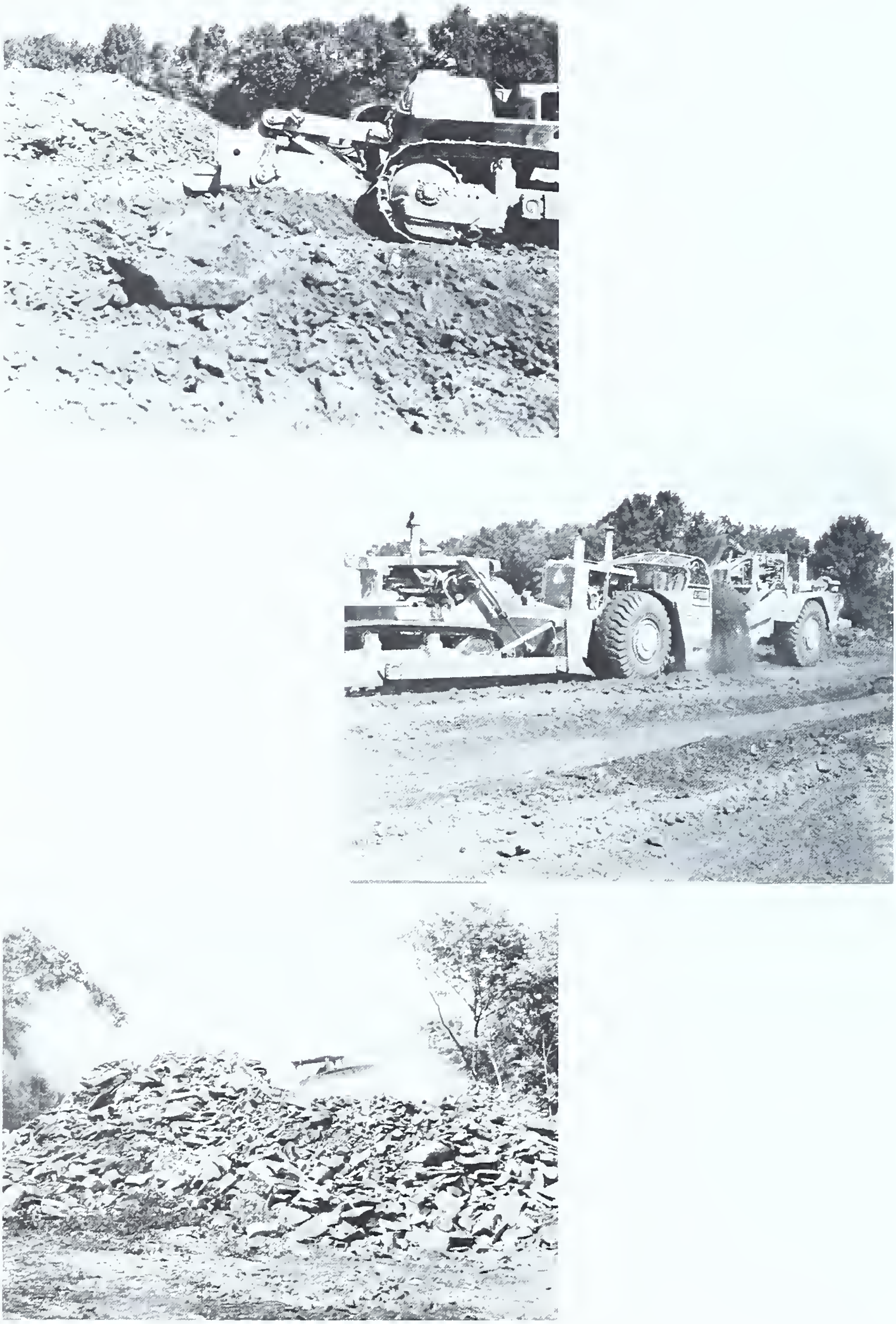


Figure 21. Examples of modern earth-moving equipment. At the top, a hydraulic tractor-mounted ripper excavates rock. In the middle, a bulldozer assists a dual-engine, wheel tractor-scraper. At the bottom, a bulldozer moves freshly blasted rock.

Building construction may suffer from landslides in several different situations. First, where buildings are located on poorly compacted, artificial fill there is a strong possibility of slope failure or fill settling. There are numerous examples throughout the state of cracked and damaged buildings, the foundations of which are located on unstable fill that is undergoing progressive failure by creep or embankment slumping.

Also particularly notable in western Pennsylvania is building construction on naturally unstable ground and on old landslides and slide scars. The existence of this condition is often not apparent to casual observation until construction stops and the ground moves. In most cases, unhappy homeowners are left with cracking walls, breaking pipes, and tight windows and doors, with little or no recourse to remedial measures. Failure may be complete (Figure 22), causing total loss of a home.

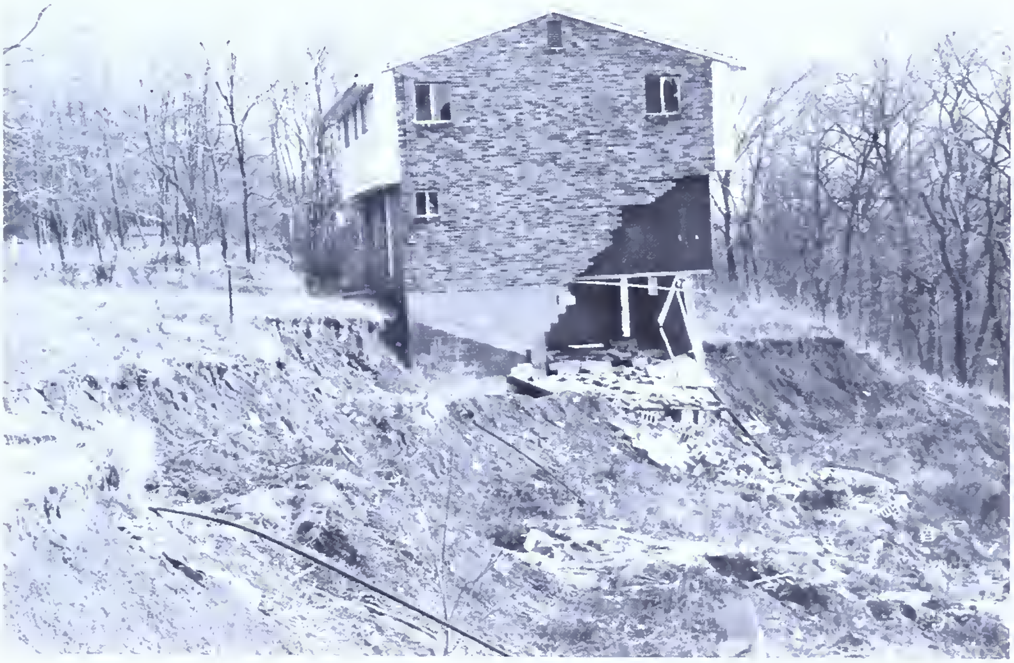


Figure 22. A new home severely damaged, and eventually totally destroyed, by slope failure. The remains of the home, now gone, are at the head of an active slide that has moved downslope, as shown on the left side of the photograph (photograph by J. L. Craft).

Lastly, there are buildings whose foundations are on stable ground but which have unstable ground upslope. These structures are subject to being damaged or overwhelmed by advancing soil, rock, and debris moving downslope onto the property.

Disruption of surface and subsurface drainage during construction can cause or trigger movement farther downslope. Generally this involves redirection or concentration of water flow at a particular site during construction, resulting in increased lubrication and fluidity of the slide-prone material.

When slopes are affected by construction and other activities of man, mass movements can and do occur outside of the areas of natural landslide occurrence identified in the previous sections.

LANDSLIDE PREVENTION/SOLUTIONS

Many natural and man-induced landslides are a direct result of failure to recognize the hazard potential. Recognizing the existence of the hazard is the most important step in controlling it. Once recognized, the hazard potential may be reduced by 1) special construction procedures, and 2) local ordinances that place limitations on development. It is desirable to have detailed maps showing individual slide-prone areas (Pomeroy, 1976) for the development of these ordinances. When a site is being considered for a project, a specific site investigation is necessary within the property boundaries for construction design as well as a general analysis of soil, rock, and groundwater factors that would be influenced by any proposed construction. Initial lack of knowledge about ground conditions at, and adjacent to, project sites throughout the state has resulted in massive slope failures and expensive remedial repairs far above initial cost estimates. Before undertaking remedial measures, the cause of a slide must be understood.

Engineering treatment to stabilize a slide or slide-prone slope may involve one, or a combination, of the following: 1) drainage modification, 2) erosion protection, 3) "toe" retainers using caisson, cribbing, rock protection, fences, or walls, 4) partial removal of slide-prone material and addition of impervious, compacted material, or 5) total removal of slide material. Developing proper drainage and making changes to existing drainage are important to slide prevention and slide stabilization because increased amounts of flow-through water are major triggering agents of downslope mass movement. Drains may be installed around the head and flanks of a potential slide to direct surface runoff away from the unstable area, or within the unstable material, in an effort to drain it. Drainage work is often combined with other methods to control unstable ground, the most common of which is retention of the toe of the slope. Deeply embedded steel posts and heavy mesh fencing along the toe have been particularly effective in the retention of rockslides and rockfalls. For retention of earthflow a concrete wall in combination with concrete or wood cribbing at the toe may provide effective retention.

Where landslides occur in otherwise stable ground that has been altered by construction, the control of mass movement is often easier to accomplish than it is in areas of naturally unstable ground. Where a natural geologic hazard exists, designing around it or leaving it undisturbed has given the best results.

SUBSIDENCE AND SINKHOLES

DESCRIPTION

Subsidence is the downward movement of surface material; it involves little or no horizontal movement. Natural subsidence is most pronounced where the bedrock consists of limestone or dolomite and is related to solution of these two rock types, which, based upon their chemical composition, are referred to as carbonate rocks. Natural surface subsidence is considered to be a geologic hazard. Surface subsidence resulting from underground mining or from excessive pumping of groundwater is not classed as a natural geologic hazard, because these activities cause otherwise stable ground to become unstable. However, the influence of the activities of man on the occurrence of this hazard is very significant and will be discussed in a following section.

Natural subsidence is expressed at the surface by the formation of sinkholes. A sinkhole (Figure 23) is a depression in the surface of the ground which results from collapse of the roof of a cave in carbonate rocks or from subsidence of surface material into subsurface openings produced by solution of the carbonate bedrock. The formation of sinkholes is dependent upon the presence of limestone or dolomite, as they are somewhat soluble in slightly acid

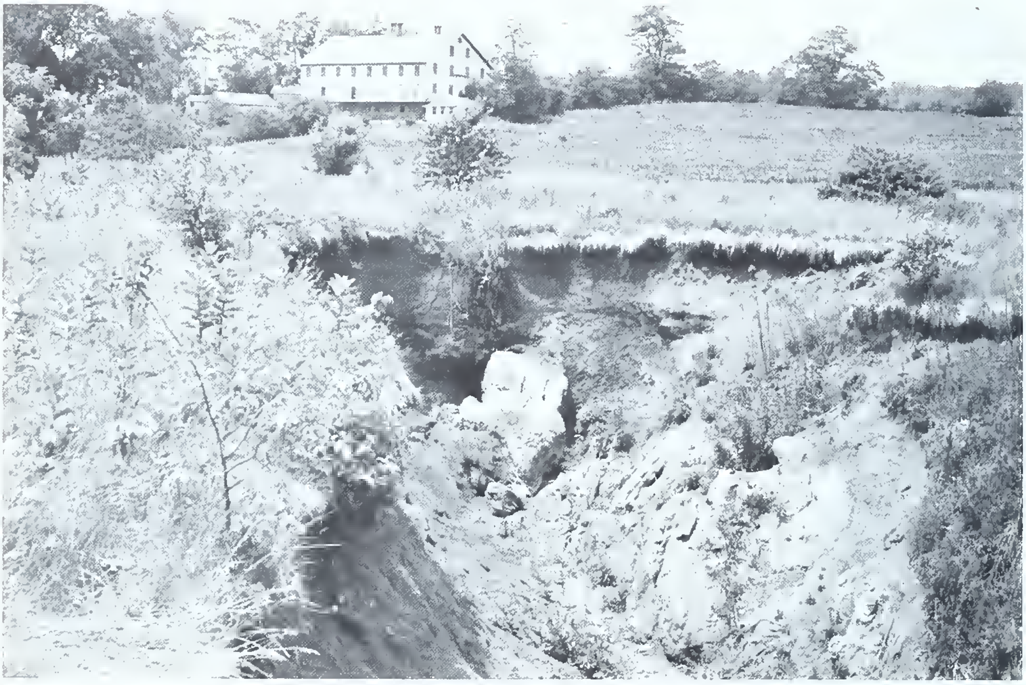


Figure 23. A large sinkhole, approximately 240 feet long, 60 feet wide, and 20 to 40 feet deep, which has deeper solution channels below. This sinkhole is one of the largest of several in farm fields that are in the path of urban expansion outside a growing Pennsylvania municipality in York County.

subsurface water. It should be noted that not all areas underlain by carbonate bedrock are subject to significant solution and sinkhole development. Carbonate rocks are composed primarily of calcium carbonate (limestone) and a combination of calcium-magnesium carbonate (dolomite) and some impurities. Both of these compounds are soluble in acid. Rainwater is slightly acidic, picking up CO_2 from the atmosphere, and becoming more acidic where decaying vegetation is available in the soil through which water passes down into the bedrock. Earth forces, working over long periods of geologic time, have folded and broken the carbonate rock, resulting in a network of joints and fractures which permits water to move many hundreds of feet beneath the surface. For many thousands of years precipitation has fallen on limestone terrains. The precipitation has seeped down through thin soil into far-reaching fracture systems. In the bedrock, two things happen: 1) the water widens the fractures by solution, and 2) a residue of insoluble material (impurities) from the rock is left behind. The insoluble material is the beginning of a residual soil which eventually extends over the irregular limestone surface and down into the cracks and voids. Vegetation grows and decays on the surface and a little more carbon dioxide and resulting weak acid is made available to water passing through the soil and into the rock fractures. After thousands of years of this slightly acidic water working slowly along ever-widening passages in the rock (Figure 24), a soil is built upon the bedrock. The rock surface becomes very irregular, having pinnacles (Figure 25) and small depressions, while the body of the bedrock is filled with openings ranging in size from a fraction of an inch to a large-sized cave, often interconnected by narrow openings to other caves. Some of these openings in turn become filled or partially filled with insoluble residue (mud) from weathering.

Streams flowing on the surface may disappear in places, as flowing surface water drops into the subsurface, moving through solution openings. Elsewhere, the subsurface water may come back to the surface as springs. In many places where the insoluble lime-

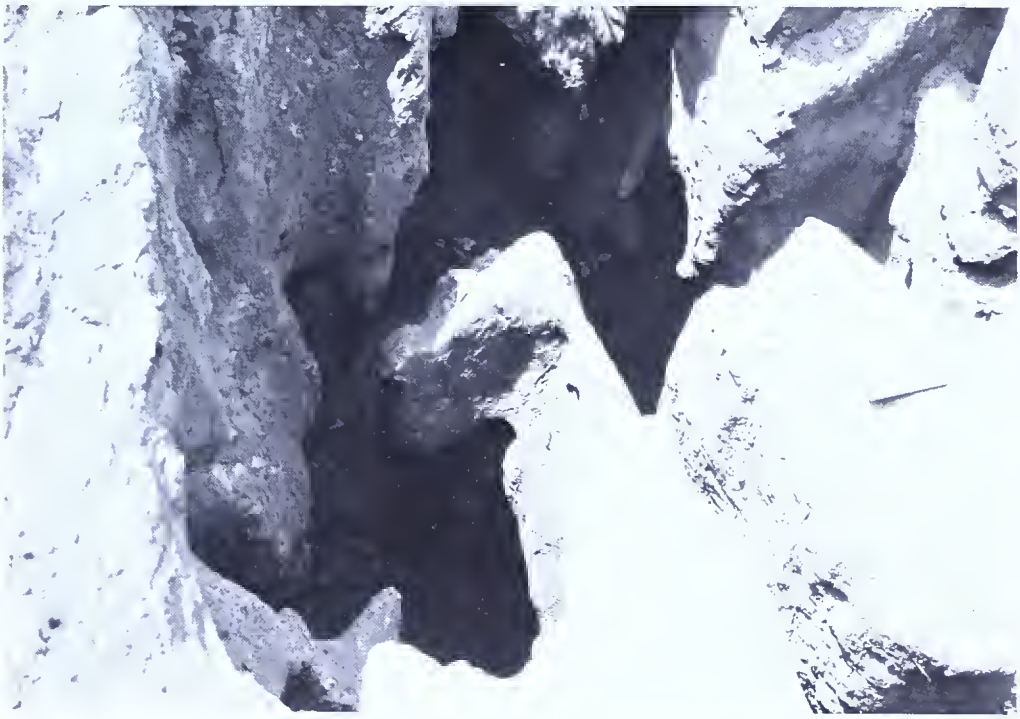


Figure 24. Solution openings, caves, and open fractures in carbonate bedrock exposed after removal of soil cover.

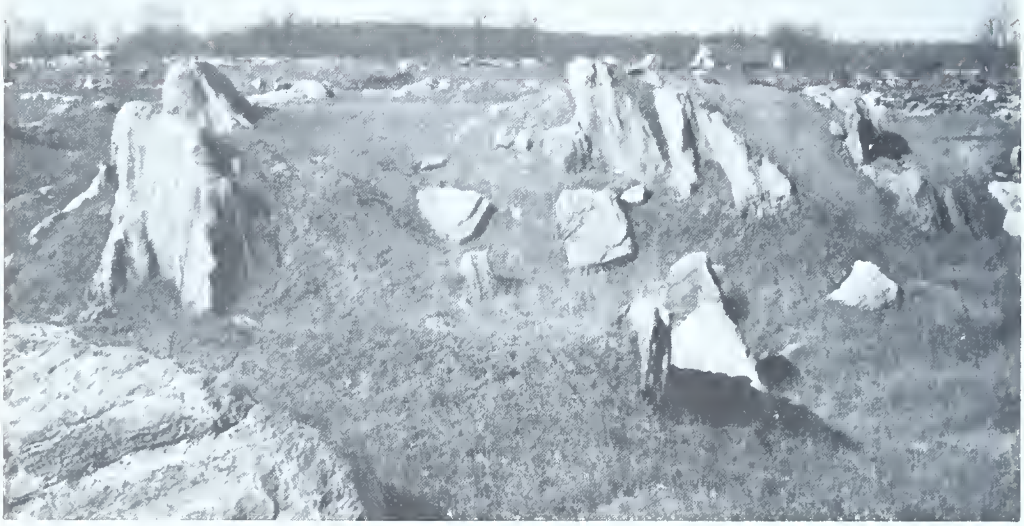


Figure 25. A relatively level field stripped of topsoil reveals the nature of the underlying limestone bedrock surface.

stone residue (mud) and groundwater fill subsurface voids, surface support is provided. When mud filling is washed away from these subsurface openings, sinkholes can form without further bedrock solution.

RECOGNITION

A fresh sinkhole often has steep sides and loose soil at the bottom (Figure 26). Sometimes bedrock pinnacles (Figure 27) or an open throat in the rock can be seen, through which subsidence took place. Sod, or trees and bushes, may sit on the loose soil in the bottom and hang in disarray from the edges. If streets, sidewalks, or lawns are involved they will hang, cracked and broken, in the open depression (Figure 28). Where bedrock is not close to the surface, the sinkhole may appear as a funnel-shaped depression in soil. An old sinkhole is not easy to identify, expressing itself as a shallow, gentle-sided depression. These can be seen in some tilled fields as depressions because they are not tillable and may pond water, and they are often filled with underbrush or trash. Ancient, healed sinkholes can defy surface identification from the ground,

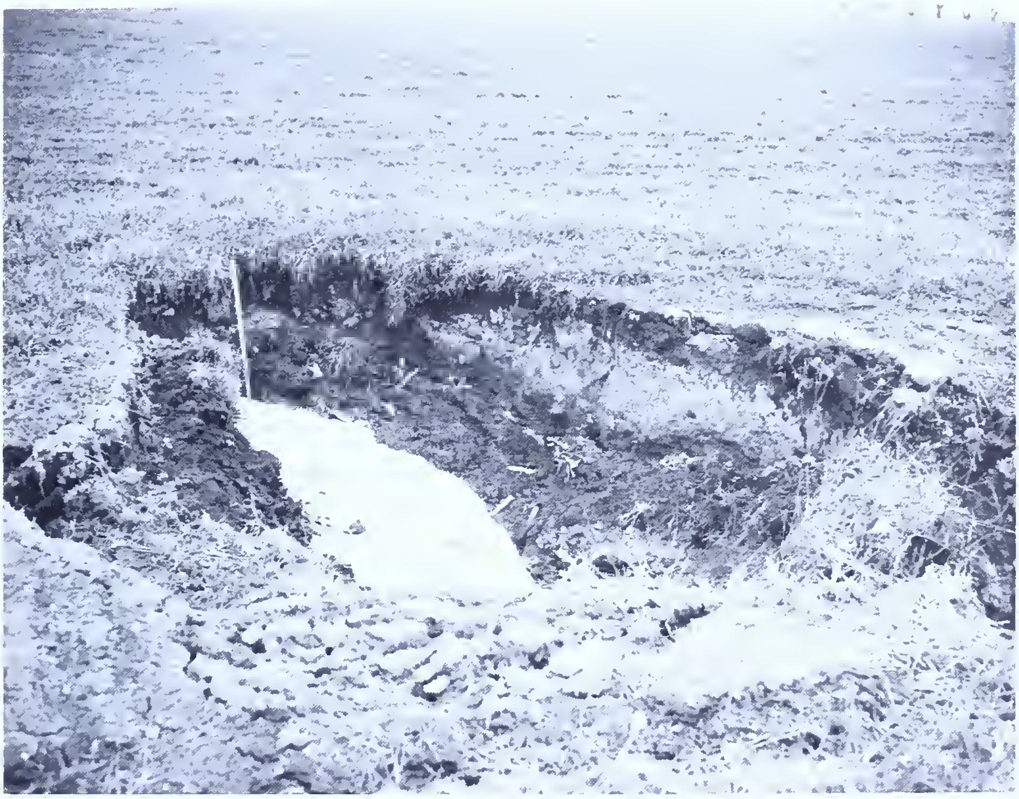


Figure 26. A newly formed sinkhole in soil above dissolved limestone.

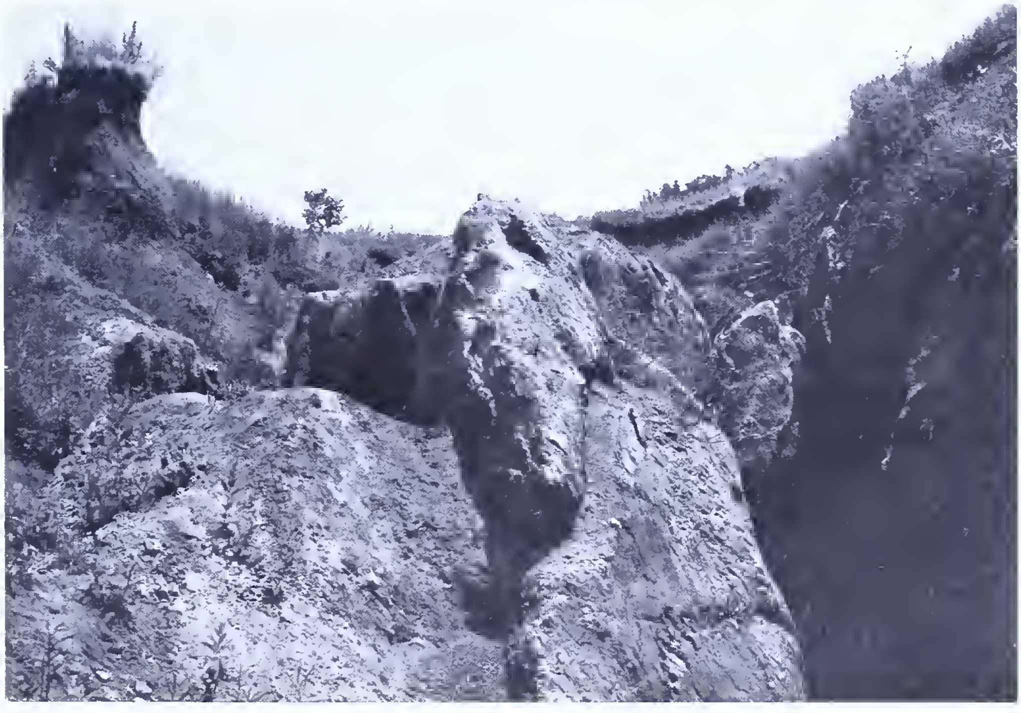


Figure 27. Pinnacles of carbonate rock forming a very irregular bedrock surface.

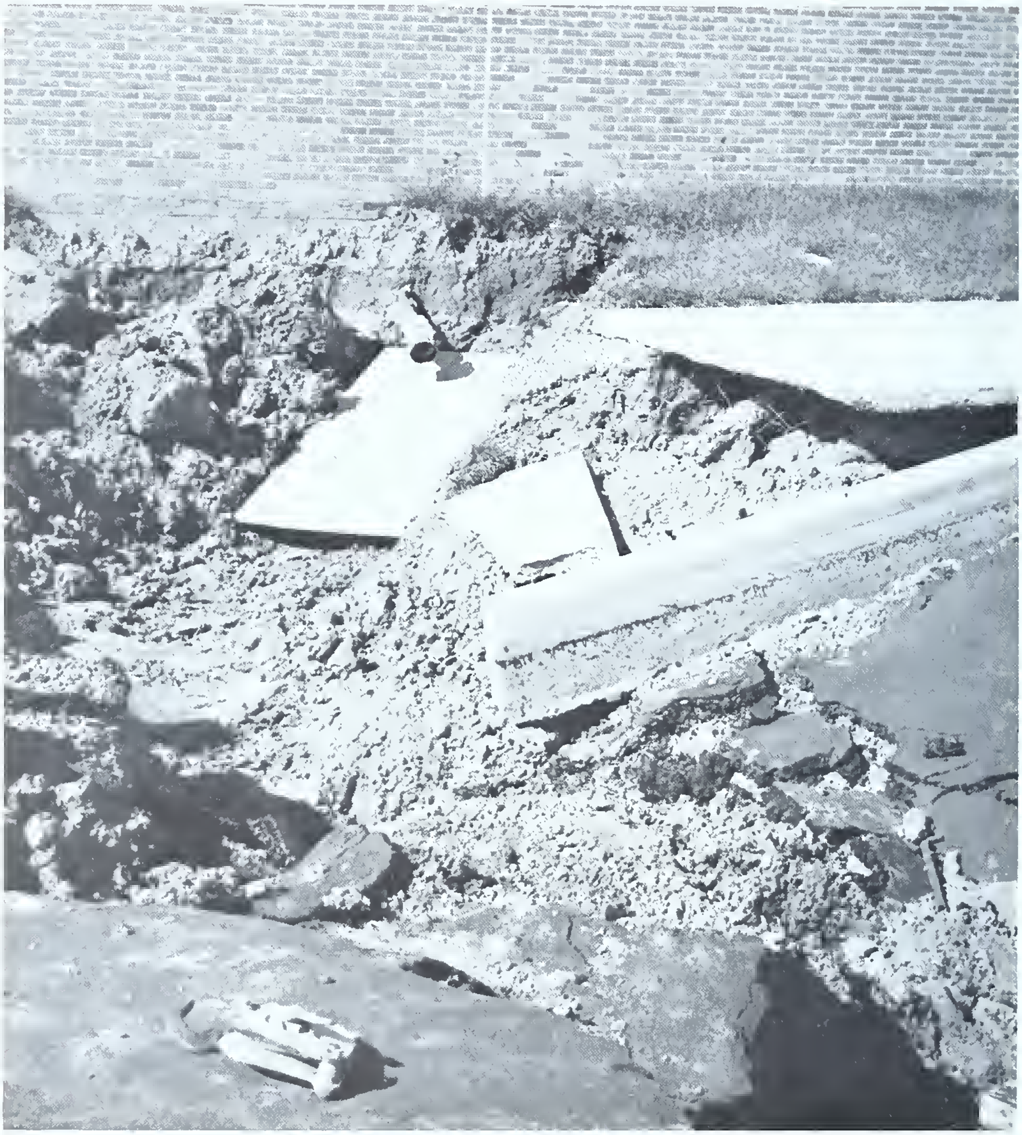


Figure 28. Broken sidewalk and curbing and collapsed pavement in a sinkhole that occurred adjacent to a new brick building.

but when an area is examined on aerial photographs, the sinkholes may be expressed as a dimpled surface or by visible changes in vegetation. Topographic maps and stereographic pairs of aerial photographs are a great help to trained observers in identifying sinkhole areas.

Some subsidence in carbonate terrain does not result in sinkholes. Because of bedrock solution there is a removal of support, but there may be no formation of a distinct area of collapse into a hole. Instead, there is differential ground movement seen most readily as cracks in soil, streets, foundations, or walls.

HAZARD

Sinkholes cause many types of damage, ranging from small misalignments to total collapse (Figure 29). The damage may occur progressively over a long period of time or, more often, very suddenly in a short period of time. When slight damage, such as a sag in a street, is definitely related to a sinkhole, there is always the concern that it will progress and become worse (Figure 30), growing into a larger problem.

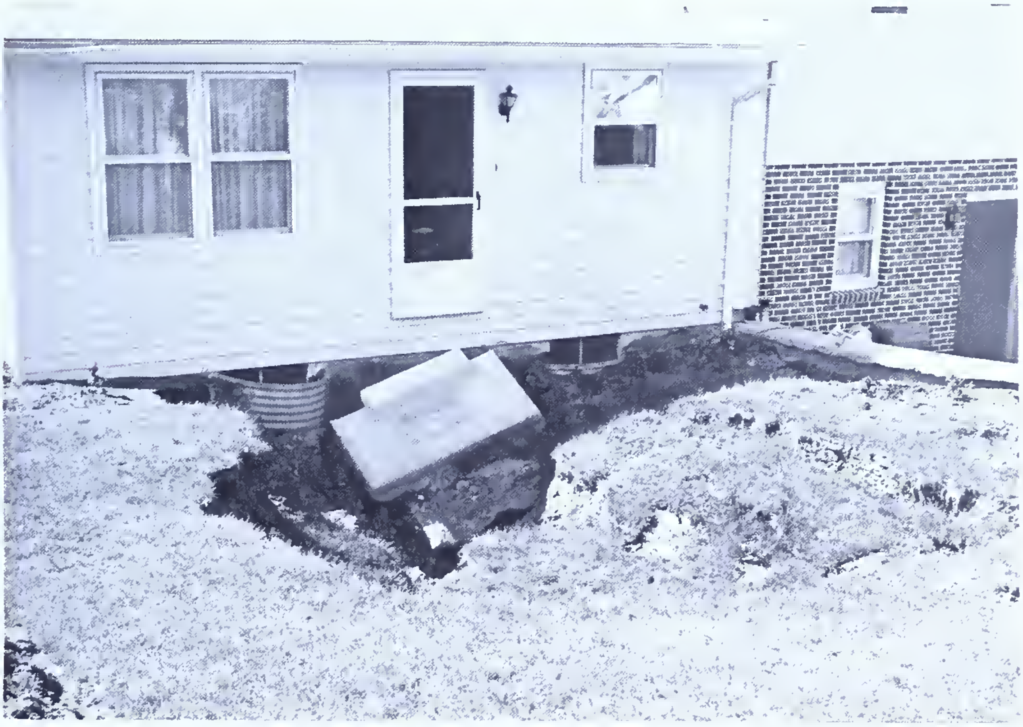


Figure 29. A sinkhole collapse adjacent to a home. Ground subsidence and removal of soil support around the foundation reflect the sinking of soil into bedrock openings beneath the structure.

Homes and other buildings, roads, utilities, water supplies, and septic systems, as well as dams and other engineered structures, in areas prone to sinkhole development are all subject to damage. When the sinkhole develops slowly it may first be seen in misaligned curbs, cracked foundations and walls, or jammed windows and doors. More often a sinkhole occurs rapidly in a few hours or a few days. If it is in a field or woods away from structures and utilities it may pose only an annoyance, perhaps causing turbidity for

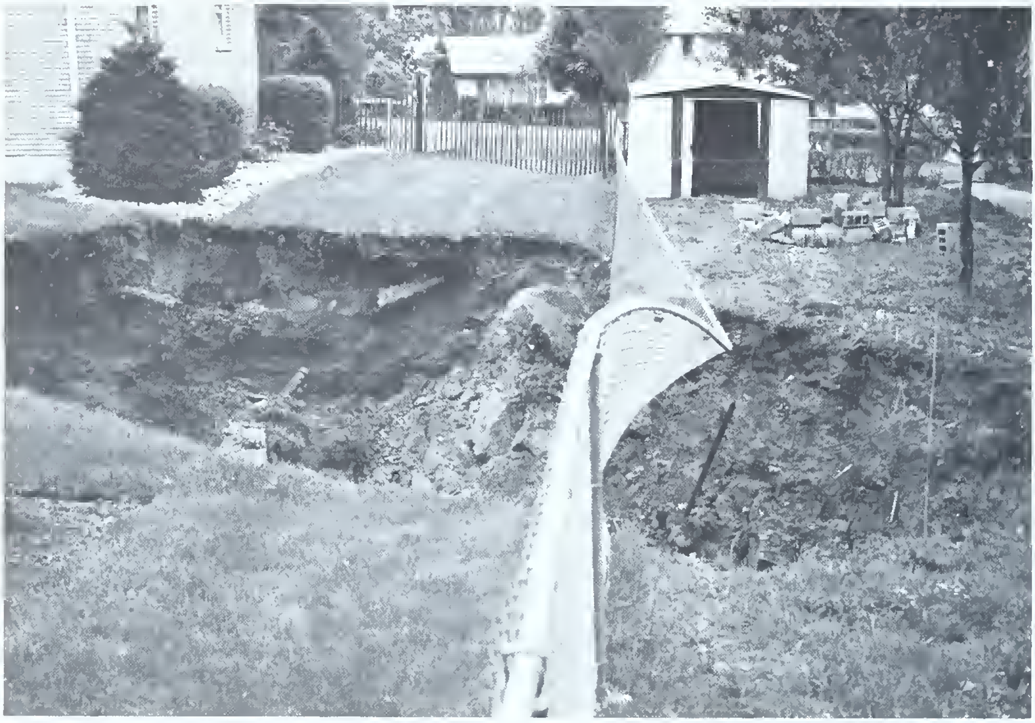


Figure 30. A large sinkhole on the property line between two homes caused extensive damage to both structures and made one of them uninhabitable. No bedrock pinnacles appeared in the bottom of the sinkhole.

a time in any nearby well and a hazard to grazing livestock. If it is in an area where there are any works of man, costly damage can result. First, buried utilities sag and are cracked or ruptured, cinderblock walls lose support and crack, and, as a building subsides, inside plaster cracks and falls. Then floors buckle, facing material falls away, and, as the situation worsens, total collapse may occur.

OCCURRENCE

Causes of sinkhole occurrence in a particular area are related to the amount of bedrock solution that has taken place and to the degree of support that remains by soil and water filling of bedrock voids. Figure 31 is a map of Pennsylvania showing areas where the bedrock at the surface consists of limestone and dolomite, as well as areas of western Pennsylvania where limestone and dolomite occur at shallow depths in the subsurface below other rock types. The principal areas of concern for sinkholes and subsidence are shown in red, forming a pattern of distribution from Bedford, Blair,

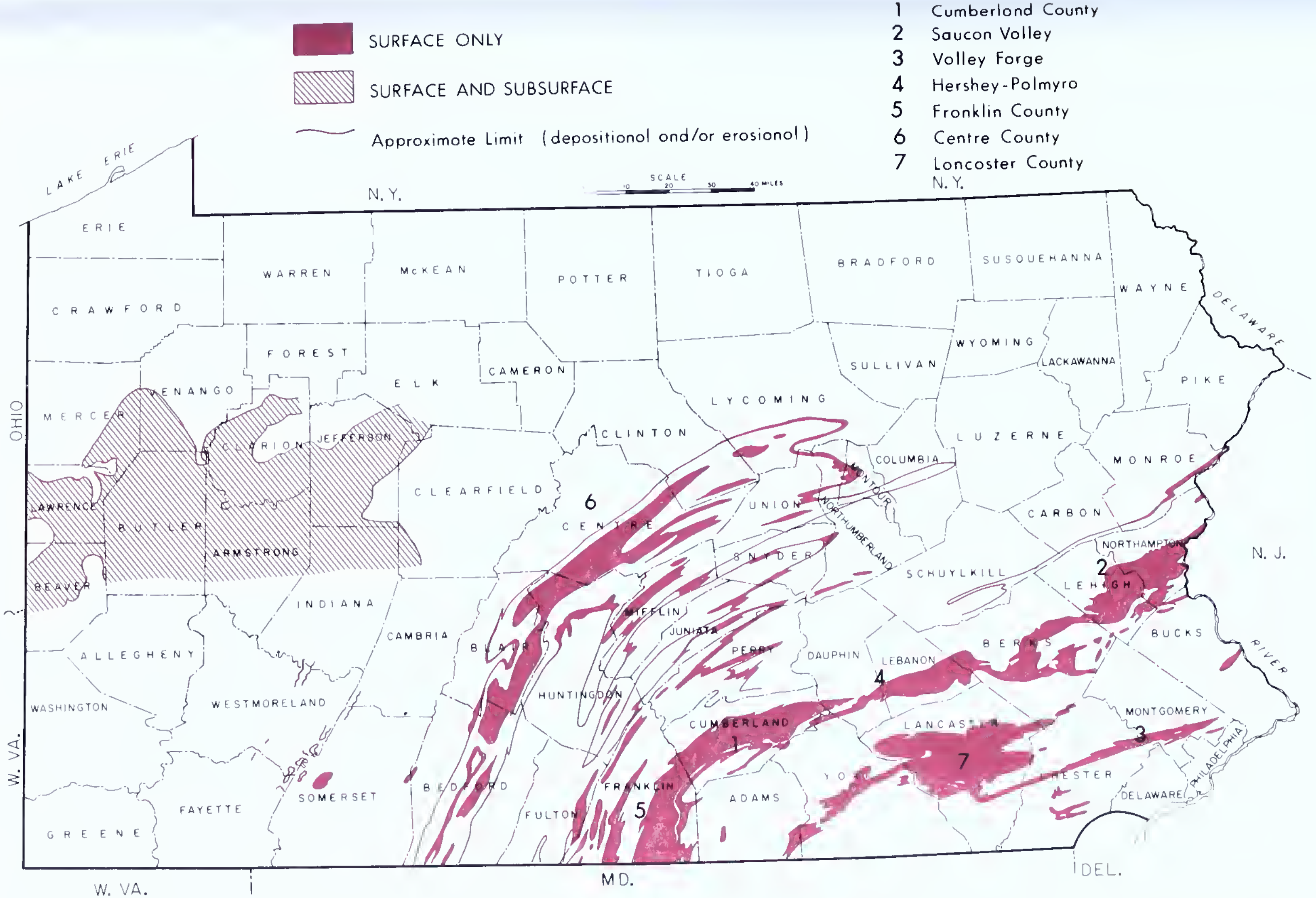


Figure 31. Limestone and dolomite distribution in Pennsylvania. Numbers indicate areas of outstanding sinkhole occurrence.

Centre, and Clinton Counties to the Philadelphia area. Numbers on the map indicate areas of outstanding past sinkhole development.

Within these areas that have a long record of sinkholes, additional sinkholes may develop when the level of the water table in the ground changes, causing soil plugs and fracture fillings to wash out (Figure 32). During and immediately following periods of heavy precipitation, the groundwater level will rise and then start slowly down. This fluctuation may wash out soil plugs in the rock, providing a channelway for the material above to be washed into voids below. Also, a period of prolonged drought will cause the groundwater level to drop, allowing clay fillings and plugs to dry, shrink, and fall out, causing collapse at the surface.

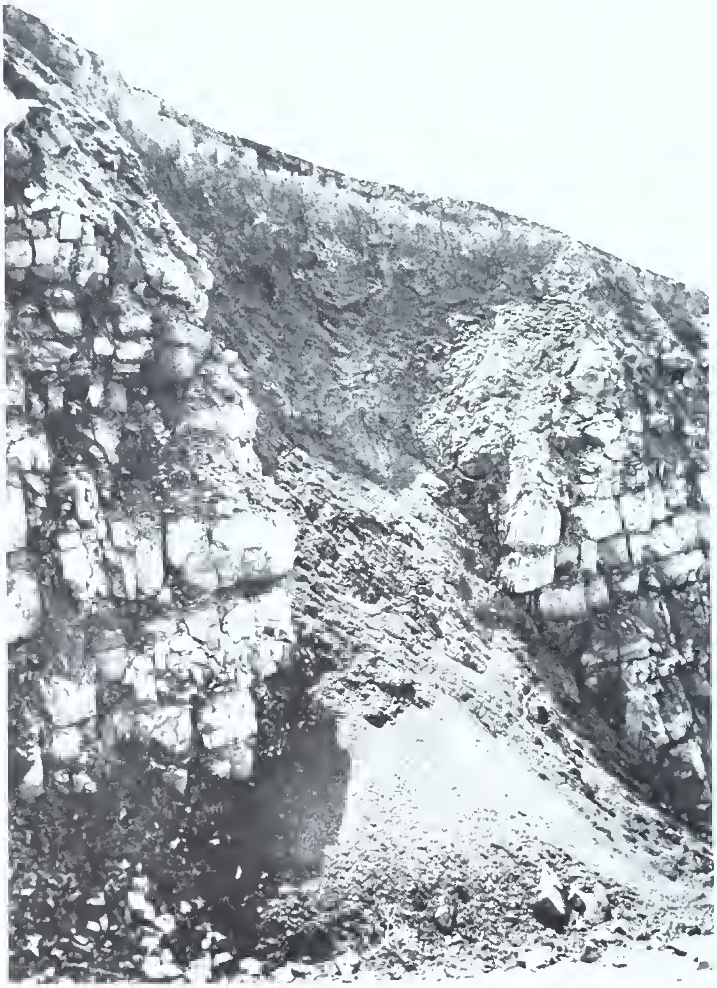


Figure 32. A roadcut cross section of a sinkhole in limestone. Material that made up a soil plug slid out after the roadcut was made.

MAN-INDUCED SINKHOLE PROBLEMS

Foundation Problems

Limestone and dolomite are predominant rock types in the broad, highly developed valleys of central and southeastern Pennsylvania. The carbonate rocks provide problems, as outlined above, but also provide desirable industrial and domestic groundwater resources, valuable mineral deposits, rich farmland, and favorable corridors for highways and railroads. Heavy use and hidden bedrock conditions can combine, however, to cause costly problems. A great many occurrences of sinkholes and subsidence in Pennsylvania can be attributed to the works of man. These are exemplified by the following two examples, one of building construction and the other of highway construction.

A large national manufacturing concern wanted to put a plant in the eastern United States. A location 20 acres in size in the Conestoga Valley (no. 7 on map, Figure 31) was chosen and building design started. Foundation drilling revealed the presence of solution cavities in limestone bedrock, the surface of which was extremely irregular beneath a relatively flat looking soil surface. Intermixed with the soil on the irregular bedrock were numerous large limestone boulders. A well-compacted soil base was necessary for the structure; therefore, in order to stabilize the foundation, over-excavation was done around the rocks and several thousand cubic yards of concrete were placed in pockets and voids. This produced a flat base from which to start, but the big problems were deeper.

Heavy rain fell for a few days after the building was finished and sinkholes began to appear around the site, on the lawn, in the parking lot, under the access road, and beneath a water main. There were 20 small sinkholes from which the soil overburden had washed away into subsurface solution channels.

A review of the topography showed that the plant was situated in the center of a shallow depression somewhat more than twice the size of the 20-acre property, out of which there was no surface drainage. Prior to construction on the site, water that accumulated in the depression percolated slowly through the soil cover. Disruption of the soil and concentration of runoff from the building and parking lot into dry wells intensified the flow, resulting in extensive sinkhole development and property damage. It was necessary to fill the sinkholes and install a system to collect most of the runoff from the building and parking lot, diverting it to the nearest stream. All of this was done at a cost equal to about half the amount of initial building construction (Knight, 1971). This example is representative of a geologic problem that can occur where there is carbonate bedrock and is indicative of what can happen when a barely stable rock and soil is affected by building construction. It also demonstrates the need for adequate geologic evaluation of a proposed construction site.

Highway construction in the Chester Valley (no. 3 on map, Figure 31) suffered from recurring sinkhole development and subsequent collapse. After initial construction, a sinkhole developed under a portion of the new road adjacent to an inactive limestone quarry. Loose material was removed from the sinkhole and a concrete plug installed, over which the highway was rebuilt. Two months later the roadway collapsed again and was repaired a second time, only to collapse again within a week. A temporary roadway was built around the subsidence area and the sinkhole in the original right-of-way was observed to collapse six more times in a 10-month period. The area of subsidence was 100 feet in diameter, and the biggest individual sink in that area was 35 feet in diameter and 30 feet deep. The temporary roadway was in use for more than four years, during which time the area was finally stabilized by the installation of alternate layers of woven steel bands and crushed stone spanning the collapse. The cost was approximately $2,000,000 to repair 1100 feet of roadway.

This illustrates how difficult and costly the remedial treatment of sinkhole problems can be. To permanently design around this problem was not feasible because the area is urbanized and route selection was limited. Widespread limestone solution was indicated by examination of the quarry walls; the area has been described (Fergusson, 1974) as follows: "Many solution features are observable along the east wall including a cross section of a large sinkhole near the center of the wall. A red clayey soil rests on the weathered dolomite surface and fills the voids between the pinnacles. The clay has been washed down solution channels and solution enlarged joints deep into the subsurface."

A detailed study of joint trends and abundance and size of subsurface openings was undertaken after the many subsidences at the site. This was done by core boring and geophysical methods involving the resistivity of rock, clay, soil, water, and void space to the passage of electric current. Although the exact size and spacing of subsurface voids could not be outlined, the magnitude of the problem was defined and those remedial measures described above were undertaken.

Groundwater Pollution

Carbonate rocks are important sources of groundwater in Pennsylvania, yielding millions of gallons to commercial and domestic wells. However, due to the fact that water moves readily from the surface down through solution cavities and fractures with very little filtration along the way, groundwater in limestone is frequently polluted.

A pollutant, such as sewage effluent, which seeps untreated into the ground over a carbonate terrain may be rapidly spread over relatively long distances, in some cases several miles, through solution channels and fractures. Upon reaching the groundwater table a contaminant can move some distance away from the initial spill and can adversely affect the quality of well water for a long time. There are numerous instances in Pennsylvania of untreated domestic sewage, as well as gasoline spills and pipeline leaks, having polluted groundwater supplies and having adversely affected private water wells.

Groundwater Pumping

The extraction of mineral resources from limestone and dolomite may involve special problems when mining or quarrying extends below the water table. Figure 33 shows a stream that flowed naturally through a quarry area. In order to keep it from flooding the quarry workings as they were deepened, it became necessary to channel the flow through open conduits and pump groundwater from the lowest part of the quarry.

In another area, it is necessary to pump great quantities of groundwater from underground mine workings. These pumping operations, which go on for years, lower the natural groundwater table, removing surface support provided by water-filled voids and allowing the drained area to dry and shrink. The result is the formation of numerous sinkholes and subsidence at the surface, affecting homes, schools, roads, and land.

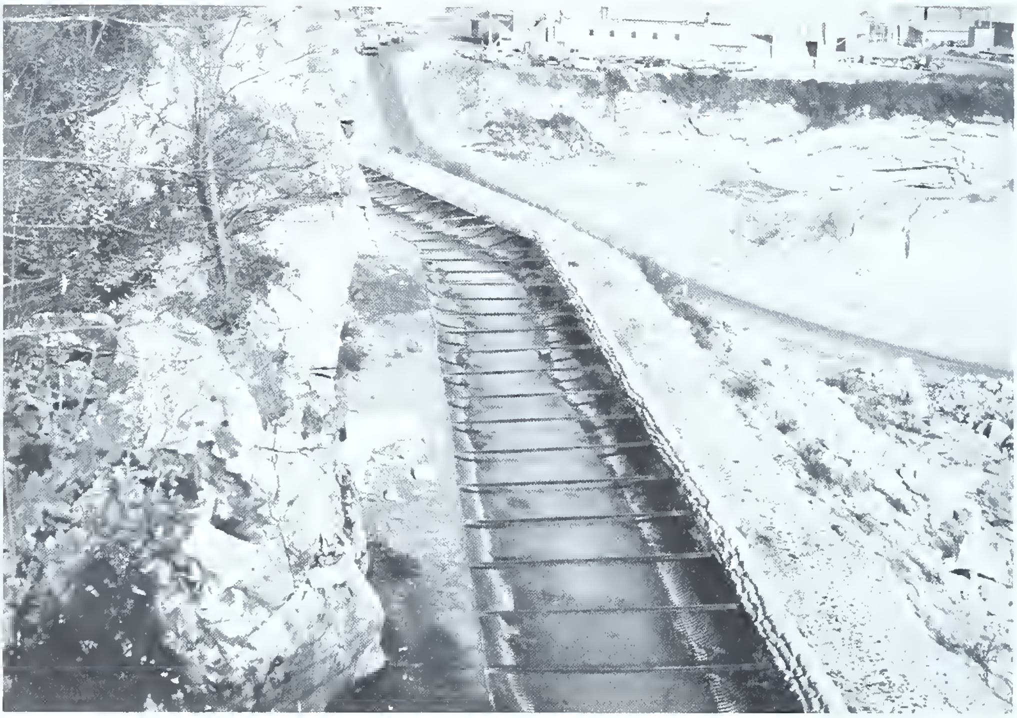


Figure 33. A surface stream carried by a half-moon, corrugated metal channel along a bench on a quarry wall. The quarry excavation is well below the level at which the stream originally flowed through the property.

PREVENTION/CORRECTION

As with landslides, most often it is the lack of awareness of the hazard of subsidence that leads to the greatest problems. This is particularly true in residential development but, as illustrated by the examples, is not uncommon for industry and highway construction.

To recognize the potential hazard one should first know what kind of bedrock occurs at the site of interest. If bedrock is limestone or dolomite it may be prone to sinkhole development or it may not. Careful examination of the drainage pattern to find interrupted streams and lack of through surface drainage in the general area may indicate that surface water is draining off rapidly into the subsurface and that solution openings are present. Next, an examination of the topography may show gentle depressions having no surface outlet, signifying a sinkhole potential. Whether positive surface evidence is found or not, a true picture of subsurface conditions can only be made by core drilling and to a limited extent by geophysical methods. Even drilling may not give an accurate picture, because, where there are voids, mud-filled fractures, and solid rock at various levels in the bedrock, technical difficulties in core drilling may arise, making it difficult to get an accurate recovery of subsurface material and resulting in a distorted picture.

Repairing a Sinkhole

There is no such thing as a typical sinkhole and, therefore, no standard way to repair one; each has its own characteristics (Figures 23 and 26). Many times repair is not a complete cure. In general, however, all loose collapsed material should be excavated from the sink in an effort to locate firm bedrock on which to anchor beams, bridging the collapse. Then a concrete mat can be placed over the area and the ground backfilled to grade using compacted soil in order to deter infiltration of water. In some cases, particularly where the soil cover is thin, a throat is found in the bedrock. This can be filled with large boulders and backfill concrete to block the throat, and then the hole can be filled to grade using compacted soil.

Sinkholes in which no bedrock is encountered (Figure 30), where the soil cover is thick, call for careful geologic analysis followed by various types of repair, ranging from pressure grouting in the subsurface to driven piles having concrete caps and gravel-mat backfilling.

Sinkholes should never be filled with any available material dumped in haphazardly. The unsightly evidence may be hidden when this is done, but a channelway for water percolation will have been created which may trigger fresh subsidence.

EARTHQUAKES

The crust of the earth is under stress at various places and, periodically, sections of it crack and readjust as stress relief takes place. Not a day passes without a significant earth vibration occurring somewhere in the world. Intensity ranges from very minor vibrations, recorded only by sensitive instruments, to great quakes causing considerable death and damage. Although earthquakes occur whose epicenters are in Pennsylvania and vibrations from earthquakes outside the state are felt in Pennsylvania, these have all been relatively minor occurrences within our state and have not caused injury or serious property damage. This state is not in a zone of moderate or high earthquake intensity (Figure 34) and therefore earthquakes are more of an alarming curiosity than a geologic hazard.

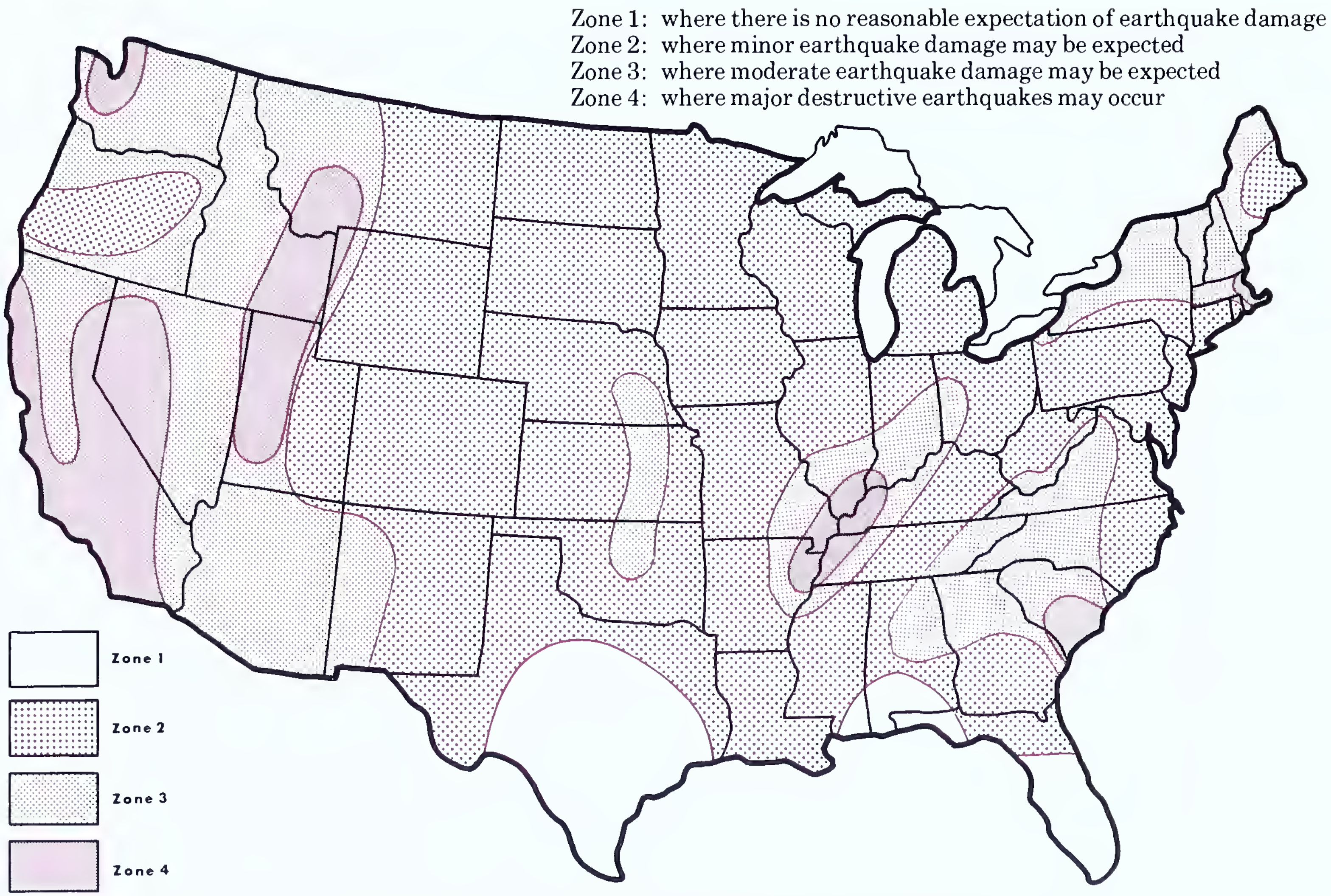
Earthquakes that have been felt in Pennsylvania have awakened people at night, shaken or broken dishware, and in some cases have cracked plaster and building facing and broken chimneys.

Rockfall from cave roofs occurs where there are broad areas of limestone and dolomite bedrock, as there are in the Great Valley and Appalachian Mountain sections of the Valley and Ridge province. It has been reported that shock waves from large blocks falling from the roofs of solution cavities in the Great Valley have been felt by local residents and were mistaken for earthquakes caused by faulting.

The first recorded earthquake to have affected Pennsylvania occurred in 1737; it toppled chimneys in New York City and was reported to have been felt in Boston, Massachusetts, Philadelphia, Pennsylvania, and New Castle, Delaware (Von Hake, 1976). In the past 30 years there have been 10 minor earthquakes in Pennsylvania; stronger quakes occurred in the Philadelphia area between 1800 and 1840. Other quakes in the commonwealth have been felt at York and Harrisburg in 1889; Allentown in 1884 and 1908; Erie in 1934; Wilkes-Barre and, later in the year, Sinking Spring in 1954; the Lehigh Valley in 1961; Blair County in 1938, 1954, and 1964; Philadelphia in 1973; and Lancaster County in 1972 and 1978.

The most widely recorded earthquake occurrences in North America were centered in Missouri in 1811 and 1812. Shocks were felt over an area of 2 million square miles from Canada to the Gulf of Mexico and from the Rocky Mountains to the Atlantic Ocean. There were three great earthquakes centered in New Madrid, Missouri. They happened on December 16, 1811; January 23, 1812, and February 7, 1812. Each was felt by the people of Pennsylvania. Damage in Missouri was light because the quakes centered in an area sparsely populated at the time.

Another great earthquake felt in Pennsylvania occurred in Charleston, South Carolina in 1886. It was felt over an area of almost 2 million square miles, from Bermuda to Maine and from the East Coast to the Mississippi Valley. From readings of Modified Mercalli 10 at Charleston, the vibrations subsided to MM 4 in Penn-



Zone 1: where there is no reasonable expectation of earthquake damage
Zone 2: where minor earthquake damage may be expected
Zone 3: where moderate earthquake damage may be expected
Zone 4: where major destructive earthquakes may occur

Figure 34. Seismic risk map of the United States (after Algermissen, 1969).

sylvania, giving the state a moderate shaking. Substantial quakes centering in the Gulf of Saint Lawrence have also been felt here.

SUMMARY OF PENNSYLVANIA'S GEOLOGIC HAZARDS

While generally not well publicized, an examination of the records at government agencies, in newspaper reports, and from other published information shows that the most frequent geologic hazards to be concerned about in the commonwealth are landslide features and sinkholes. Changes in the state of the earth's surface are always taking place, slowly in some areas and rapidly in other areas. These changes often create instability resulting in such features as landslides and sinkholes. In many areas of the state the works of man have also triggered landslide or sinkhole development, pointing to the need for careful geologic studies of the project area as part of any construction program.

A potential geologic hazard, commonly hidden from view, may not have the same investigative appeal embodied in a potential mineral resource. However, in dollars and cents, the geologic danger that is identified and alleviated can save money, even as a valuable mineral resource can make money. Total cost figures resulting from geologic hazards are unavailable over an extended period of time, but a few outstanding examples of known damage costs that could have been avoided give striking testimony to the magnitude of geologic hazards in Pennsylvania.

In Allegheny County, which encompasses greater Pittsburgh, with its rapid development and high landslide potential, loss from landslides has been approximately 2 million dollars per year since 1945; during that time there has been an increase in the incidence of landslides because of the expansion of development into geologically unstable areas. On a new four-lane highway in Blair County, 250,000 cubic yards of mountainside slid rapidly onto a completed portion of roadway not open to traffic at the time; the cost to remove the earth and debris slide exceeded $300,000. During construction of a large highway interchange in an area of limestone bedrock in central Pennsylvania, 34 sinkholes were encountered; this was more than had been anticipated during foundation investigation, causing considerable delay and requiring corrective action at a cost far greater than the contract estimate.

These and other difficulties, directly related to the rock on which we build, have been costly in money, time, injury, and even death. The relationship of our growing society to the surface of the earth on which it lives is exceedingly important. Potential geologic problems, therefore, warrant the consideration and attention of each of us.

GLOSSARY

Bedrock. A general term for the solid rock that underlies soil or other unconsolidated, superficial material.

Boulder colluvium. Large, loose rock fragments, resulting from weathering and gravity movements at the base of steep slopes and cliffs.

Carbonate rock. A rock such as limestone or dolomite, consisting chiefly of the carbonate minerals calcite or dolomite; it is a sedimentary rock composed of more than 50 percent by weight of either calcium carbonate (calcite), magnesium carbonate (dolomite), or a combination of the two.

Desiccation. A drying up or dehydration.

Dip. The angle that a rock surface makes with the horizontal.

Fault. A surface or zone of rock fracture along which there has been displacement.

Geologic discontinuity. A planar feature such as a bedding plane, joint, fracture, or fault in a rock mass that acts as a zone of weakness along which failure may occur when an excessive stress is exerted on the mass.

Gravity movement. Downward movement of rock, soil, or debris by the force of gravity.

Groundwater. Water below the surface of the earth.

Joint. A surface of fracture or parting in a rock other than a bedding plane.

Limestone. A sedimentary rock consisting of more than 50 percent by weight of calcium carbonate, primarily in the form of the mineral calcite.

MM. Modified Mercalli Intensity Scale, a scale used to measure earthquake intensity, ranging from 1 to 10.

Resistivity. The longitudinal electrical resistance per unit length of a material.

Scree. Broken rock debris. Equivalent to talus.

Seismic. Pertaining to an earthquake or earth vibration.

Sinkhole. A depression in an area usually underlain by carbonate rock; formed either by solution of the surficial limestone or by solution and collapse of underlying caves.

Talus. Rock fragments of any size or shape derived from and lying at the base of a cliff or very steep, rocky slope.

Water table. The upper surface of the groundwater zone that is water saturated; usually the underground continuation of lake and stream surfaces. It conforms in general with the shape of the land surface.

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